Superconducting Magnet Division
Magnet Note

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Title: The RHIC Magnet Electrical System* - draft 8 August 2001 – for NIM

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The RHIC Magnet Electrical System* - draft 8 August 2001 – for NIM

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The RHIC Magnet Electrical System consists primarily of the power converters that are used to energize the superconducting magnets in the collider ring, the power distribution system (both room temperature and superconducting) to deliver that power from the converters to the magnets, a detection system to monitor for quenches in the magnets and superconducting cables, and a protection system to remove power from the superconductors if a quench is detected. This system also has major interfaces with the Control System for commands, status monitoring, current setting and analog monitoring of the power supplies, and with Conventional Facilities for power distribution of the mains at and below the 480VAC level.

Introduction

The electric power supply system required to operate the superconducting magnets for RHIC falls into three categories:

The main power supplies - The supplies used to power the main dipoles and the main quadrupoles are similar in that they have a ramp power section to provide a high voltage to bring the magnets rapidly up to full field, and a holding power section to maintain that current in a precise and efficient way during beam storage.

The main dipole and quadrupole power supplies are similar in design. Both use a pair of 12-pulse, phase controlled rectifier power modules. The dipole supply requires a 400 V ramp section and a 30 V holding section, while the quadrupole system uses a 90 V ramp section and a 15 V holding section. The control and regulating system will be interfaced with the main control computer for monitoring and analysis. The digital regulation system will use as its reference a zero flux Direct Current Current Transformer (DCCT), and will also reduce the sub-harmonic component of the ripple voltage through its control of the rectifier commutation. In order to control the betatron tune within)<=10^{-3}, it is required that dipole and quadrupole currents track with about 10^{-5} accuracy.

A smaller shunting supply is used to offset the current in the horizontal quadrupole string for the current in the vertical quadrupoles string.

All main power supplies are located in the service building at 4:00 (4 o'clock).

The insertion power supplies - These include the shunts to the insertion dipoles, D0 and DX, the shunts to the insertion quadrupoles, Q1-3, and Q6-9 and the trim quadrupole supplies at CQT4, 5, and 6. They will be specified in modular sizes to minimize the quantity of types of supplies to maintain, and to simplify procurement.

The unipolar insertion supplies use 12-pulse, phase controlled power sections. The bipolar insertion supplies use switch mode power sections. While these accept a current set point digitally, the regulator is a precision analog device. All units use a DCCT, as the main supplies do, as a precision current measuring device.

All insertion power supplies are located in the service buildings.

The corrector power supplies - These include the supplies for the dipole correctors, the insertion correctors, the gamma-T jump, and the sextupoles.

These smaller supplies will either be phase controlled, or switch mode units. They will use analog regulation loops around shunt or DCCT feedback. Both the current command, and current and voltage readbacks will be analog signals.

All corrector power supplies are located in the ring alcoves.

Summaries. Table 1-1 summarizes the required power supplies, showing voltage, current, and quantity. Power supplies labeled "mono" are units that do not reverse current polarity. Units labeled "bi" are bipolar supplies, and operate with either polarity of voltage or current.

Table 1-1. Power Supply Summary

Item	Polarity	Voltage (V)	Current (A)	Quantity (2 rings)
Main Power Supplies				
Dipole Ramp	mono	400	5500	2
Dipole Flat-top	mono	30	5500	2
Quadrupole Ramp	mono	90	5500	2
Quadrupole Flat-top	mono	15	5500	2
Quad H/V Trim	mono	40	300	2
Insertion Dipoles				
Type A	mono	20	2000	14
Type B	mono	20	600	7
Insertion Quadrupoles				
Type A	bi	15	150	96
Type B	bi	15	300	14
Type C	mono	15	200	48
Type D	mono	15	300	24
Type E	mono	15	450	16
Type F	mono	20	600	16
Corrector Supplies				
Dipole	bi	20	50	468
Gamma-T pulsers	pulsed	300	40	24
Skew Quads	bi	20	50	48
Octupoles	bi	20	50	48
Sextupole	bi	100	100	24
Low Beta Triplet*	bi	20	50	56

*8 a_2, 8 b_2, 16 b_3, 8 b_4, 16 b_5 correctors.

Magnet Bus

The power supplies for the collider magnets are distributed in the service buildings and in the tunnel alcoves. All magnets, with the exception of the sextupoles and the magnets in the corrector packages, are powered from the service building. Power is carried to the magnets from the service buildings using superconductors. These superconductors are bundled into an assembly called the Cold Crossing Bus (CCB). The power leads within each sextant of a ring are carried to the service building in two CCBs, one containing the main dipole current, and the other the quadrupole current. The two CCBs are identical, except that the quadrupole CCB has one additional conductor. The CCB is also used to carry power across warm sections of the ring, such as the space between the CQ3 and CQ4 magnets.

The cross section of the CCB is shown in Fig. 1-1. Wherever the CCB is used, the currents always sum to zero. This means that the critical current rating will be based on a magnetic field of essentially zero strength. The conductors are also given a MIITs ($\int I^2 dt$) rating as a measure of how much energy the copper in the cable can withstand during a quench. Table 1-2 lists these ratings.

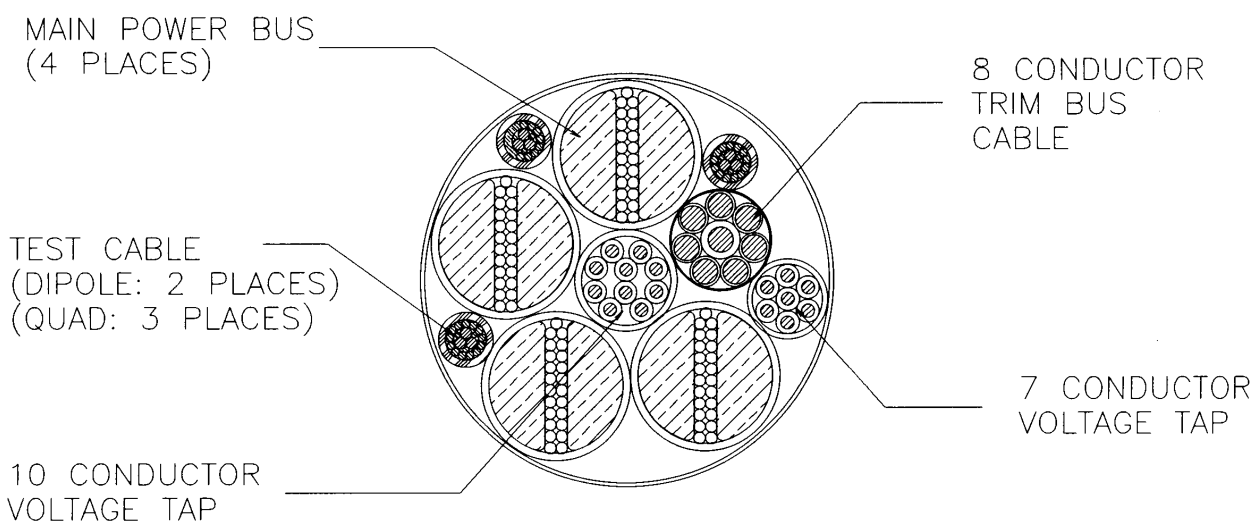


Fig. 1-1. Cold Crossing Bus

Table 1-2. Cold Crossing Bus Ratings

Conductor	Current Ratings, A Critical	Operating	MIITs (10^6 A^2 sec)
Main Power	11000	6600	204
Test Cable	1800	600	1.50
Trim Bus	1800	150	0.11

The diagrams of Figs. 1-2 and 1-3 show the dipole and quadrupole bus arrangements. The dipole circuit is powered from the 4:00 insertion region, with the return busses coming back at 10:00. Dump resistors are at 4:00 and 10:00, and are split for symmetry. The insertion dipoles, D0, and in the blue ring, DX, are connected in the return path. This keeps them near ground potential during a quench, and is done to minimize the stress on power supplies shunting them. In the quadrupole circuit, the H/V Offset also has quench protection, but it is not shown.

The quadrupole circuit is also powered at 4:00 with a return at 10:00. In this configuration, the vertical quads are powered on one bus, while the horizontal quads are on the other. This allows a trim supply to offset the current in the horizontal bus with respect to the vertical bus. The insertion quads placement is also shown here, and the circuits powering Q8 and Q9 will have the capability to offset the trim current, making the base current in the insertion quads independent of the trim setting.

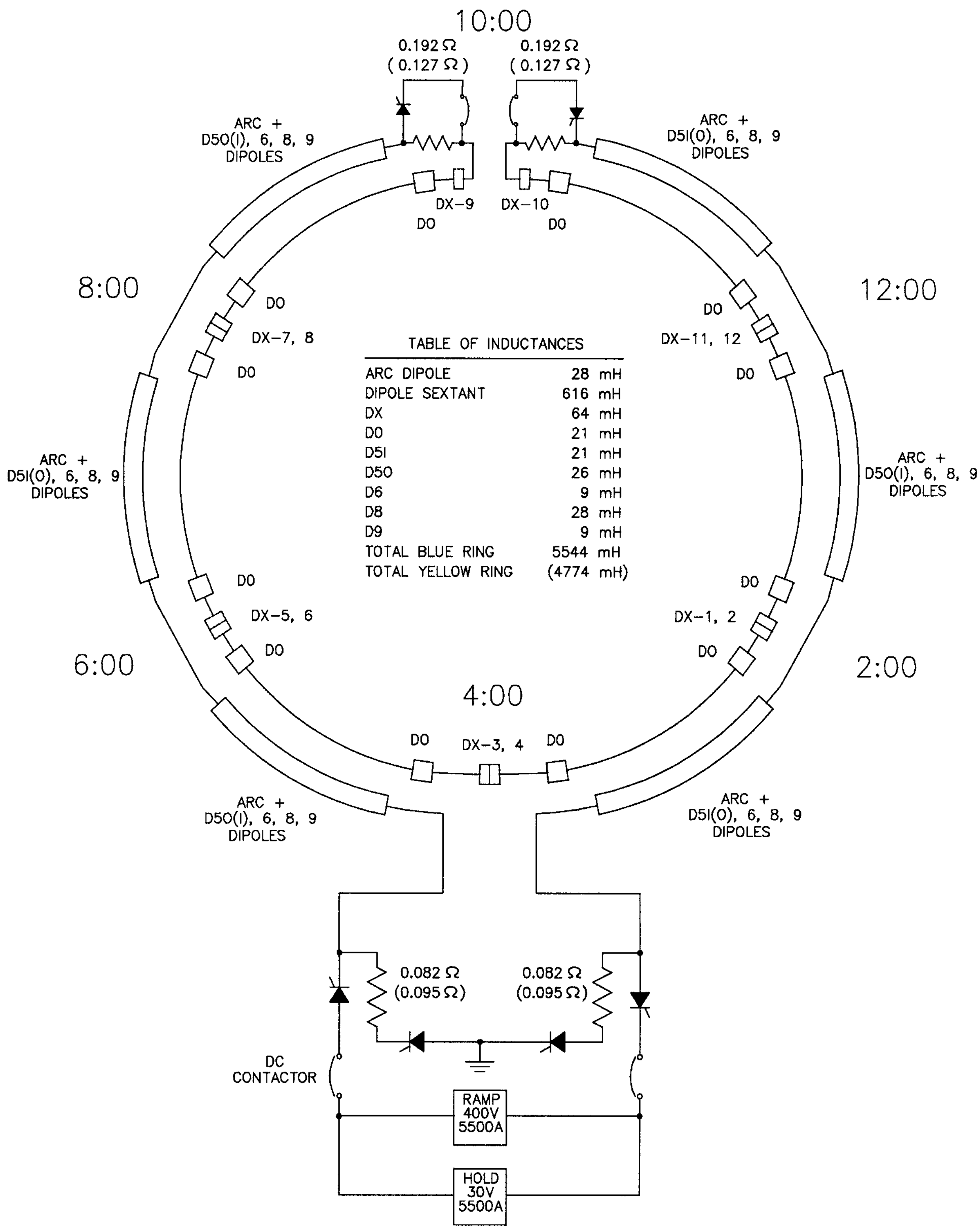


Fig. 1-2. Main dipole bus layout. The DX dipoles are in the blue ring bus only, and are shown in dotted lines.

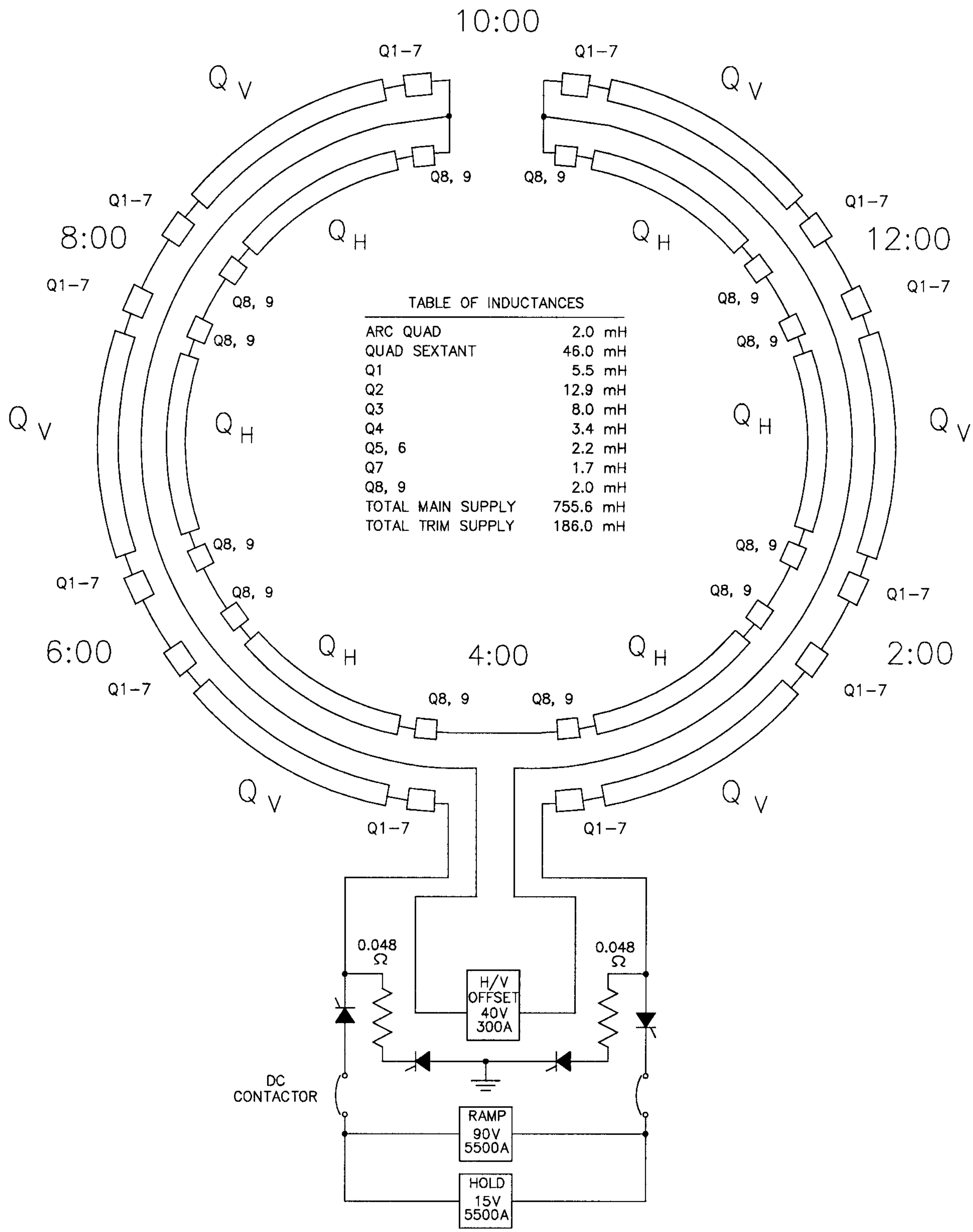


Fig. 1-3. Main quadrupole bus layout.

Cable Tray System

The power supplies for most of the superconducting magnet loads are located in the equipment service buildings. These supplies are connected to gas cooled warm-to-cold power leads, that are part of the cryogenic valve boxes, also located in the equipment service buildings. On the warm side of the power leads, copper cables connect to the power sources. On the cold side of the power leads, superconducting Cold Crossing Bus carries the current to the RHIC tunnel, where it is distributed over other superconductors to the magnet loads. The sextupole and corrector supplies are located in the tunnel alcoves, and power from these supplies is carried by conventional copper cables in trays. In addition to power supply leads,the trays also bring bema instrumentation cables and control signals to the alcoves.

In most of the ring, the trays are hung from the center of the tunnel. This is nearly directly above the magnets. The cables drop out of the trays and can either go to the power leads on the CQS assemblies, or to other devices, such as cryogenic, vacuum, and safety equipment. In those areas (typically in the region between each Q3 and Q4) where the vacuum jacketed piping bypasses warm beam tube sections, the cable trays move to the outside of the ring.

Figure 1-4 is a composite of two typical areas in the arch plate portions of the tunnel. The trays have been partitioned to segregate cable types, as required by the National Electrical Code. Each of the partitions in the tray have been labeled, and the cable types that will occupy those sections of the trays have been listed in Table 1-3.

Some cables are totally internal to the ring. They might be connections between devices in the ring or between devices in the ring and equipment in the alcoves. Other cables need to go from the equipment service buildings to the ring. These are carried by tray to the ring, where they enter at the same location as the vacuum jacketed piping. At 6, 8, 10,and 12 o'clock this means entering through the top of the ring via conduits. At 2 and 4 o'clock the tray enters through the side of the tunnel. In either case, the cables enter the tray in the ring at a location between the Q1 and D0 magnets.

The cable tray system in each sextant stretches from DX to DX, and no cables interior to the ring ever cross the beam crossing point. This avoids interference with equipment in the experimental areas.

Table 1-3. Cable Tray Space Allocation

Conductor	Total Tray Width, cm (in.) DX - Q4			Q5 - Q5		
Correctors	F,H	61	(24)	D,F,H	122	(48)
Beam Instrumentation	E,G	31	(12)	E,G	61	(24)
Vacuum, Cryogenics, Control	A	10	(4)	A	23	(9)
AC Power	B	5	(2)	B	23	(9)
Security	C	15	(6)	C	15	(6)
Totals		122	(48)		244	(96)

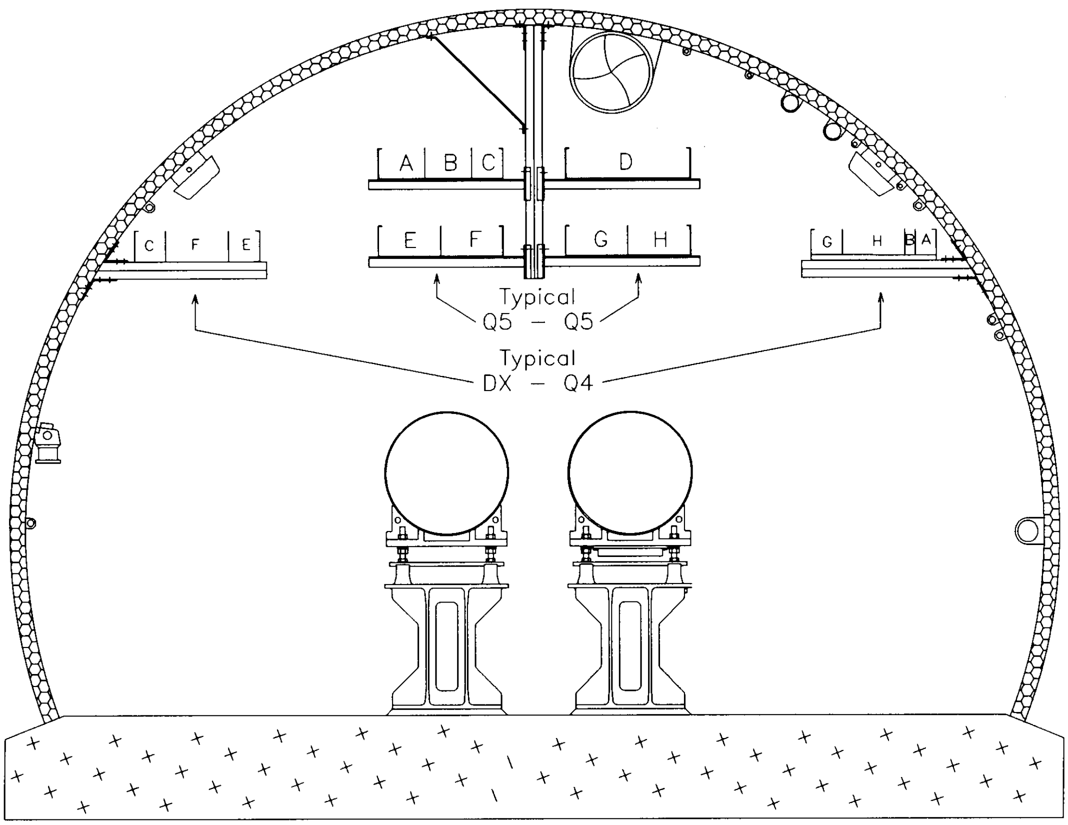


Fig. 1-4. Composite Cable Tray Layout

Quench Protection System

To prevent magnet damage in the event of a quench, the current in the quenching magnet must be reduced to zero before overheating occurs. There are two parts to this system. First, the energy from the non-quenching magnets is bypassed, through the natural switching action of a diode around the quenching magnet. Second, quench detectors "switch in" energy dump resistors that reduce the current, as they absorb the stored energy.

The single-diode bypass system is shown in Fig. 1-5. In this circuit, the current is forced out of the magnet and into the shunting diode by the natural action of the quench developed resistance of the magnet coil. Energy from the non-quenching magnets will not heat the quenching magnet because of the shunting action of the diode. The collider magnets, with the exception of the DX dipole, are able to absorb their own energy without overheating during the time that the current is being reduced by the energy dump resistors.

The DX dipole is different than the other main magnets in two ways. First, because of it's higher inductance (64 mH vs. 28 mH for an arc dipole), the induced voltage during a current ramp will be higher. This requires two series bypass diodes, instead of the single diode shown in Fig. 1-5. Second, since it cannot absorb its own energy, an active quench protection system will be required.

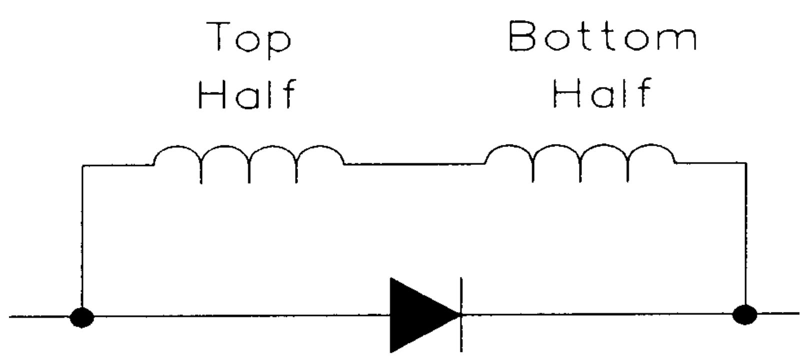


Fig. 1-5. Single diode protection circuit.

Even though the quench-inducing individual magnet is protected, it is necessary to remove the stored energy from the entire series-connected string as rapidly as possible to avoid quench propagation into neighboring magnets and to protect the bus and diodes from overheating. The thermal mass of these elements is large enough to permit a simple solution. Figures 1-2 and 1-3 show this energy extraction system.

Current is reduced in the non-quenching magnets by a redundant set of switches. The primary switches are solid state silicon controlled rectifiers (SCR). Redundancy is provided by commercially designed dc interrupters commonly used to protect large power systems. When these switches open, the current is diverted into dump resistors which dissipate the stored energy and exponentially reduce the current to zero. The bus and the diodes together with their heat sink have been tested to withstand the rated current for the worst case "dump" period.

The quench detection system is also made redundant by using two different quench detection methods. The primary method involves comparing total sextant voltages and triggering the switches when one sextant differs from the others by more than a preset limit. The detection backup is accomplished by using voltage taps on smaller groups of the magnets.

Insertion Power Supply Systems

The insertion region contains both beam bending magnet and focusing elements. To reduce power supply cost and minimize cold penetrations these elements are connected in series with the main dipole or quadrupole circuits. However, provisions are made to adjust each insertion quadrupole separately as required, either through a shunt, or an auxiliary trim quadrupole.

Insertion Dipole Power Supplies

The regular arc dipoles, and insertion dipoles D5, D6, D8 and D9 are in series with the supply side of the main dipole bus. The remaining insertion dipoles, D0, and in the blue ring, DX, are in the circuit return leg. Figures 1-6 through 1-8 shows the detailed circuit arrangement of the dipoles in the insertion regions. The quench protection assemblies and main power supplies are shown there as well. In these figures, three power supplies are shown, PS1, PS2, and PS3. They will be connected to the insertion dipoles with a link box, to allow for the best configuration of voltages and polarities for a given species combination. Table 1-4 shows the arrangement of power supplies for typical cases.

Provision for shunting current around D5 and D6 will be provided, but the lengths of these magnets will be adjusted so that no electrical correction is expected.

Table 1-4. Insertion Dipole Configuration

Power Supply	Particle	Current Rating	Polarity
PS1 - Yellow	Au, I	600 A	Reversed
PS2 - Blue	Au	2000 A	As Shown
PS3 - Blue		2000 A	Reversed
PS1 - Yellow	Cu, d, O, Si	600 A	As Shown
PS2 - Blue	Au	2000 A	As Shown
PS3 - Blue		2000 A	Reversed
PS1 - Yellow	p	2000 A	As Shown
PS2 - Blue	Cu, d, O, Si, Au	600 A	As Shown
PS3 - Blue		2000 A	Reversed

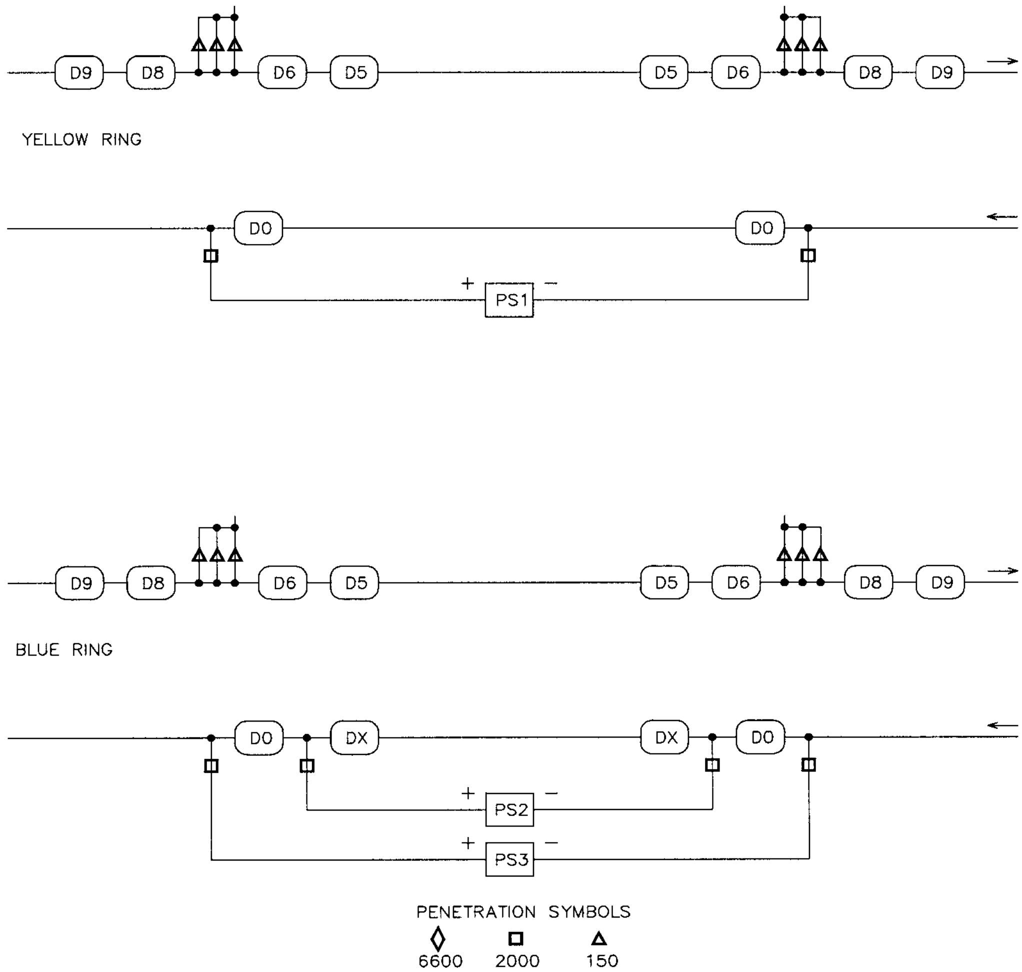


Fig. 1-6. Insertion dipoles at 2, 6, 8 and 12 o'clock.

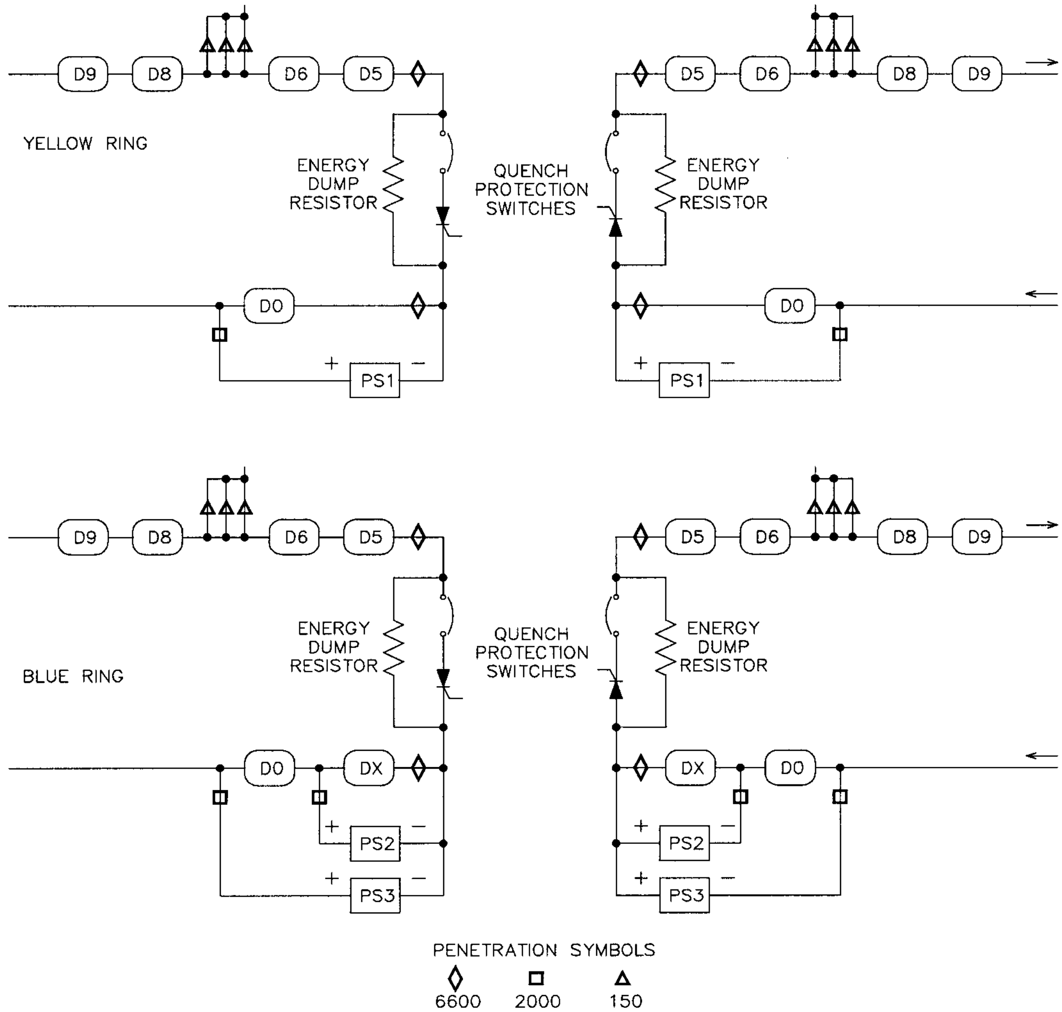


Fig. 1-7. Insertion dipoles at 10 o'clock.

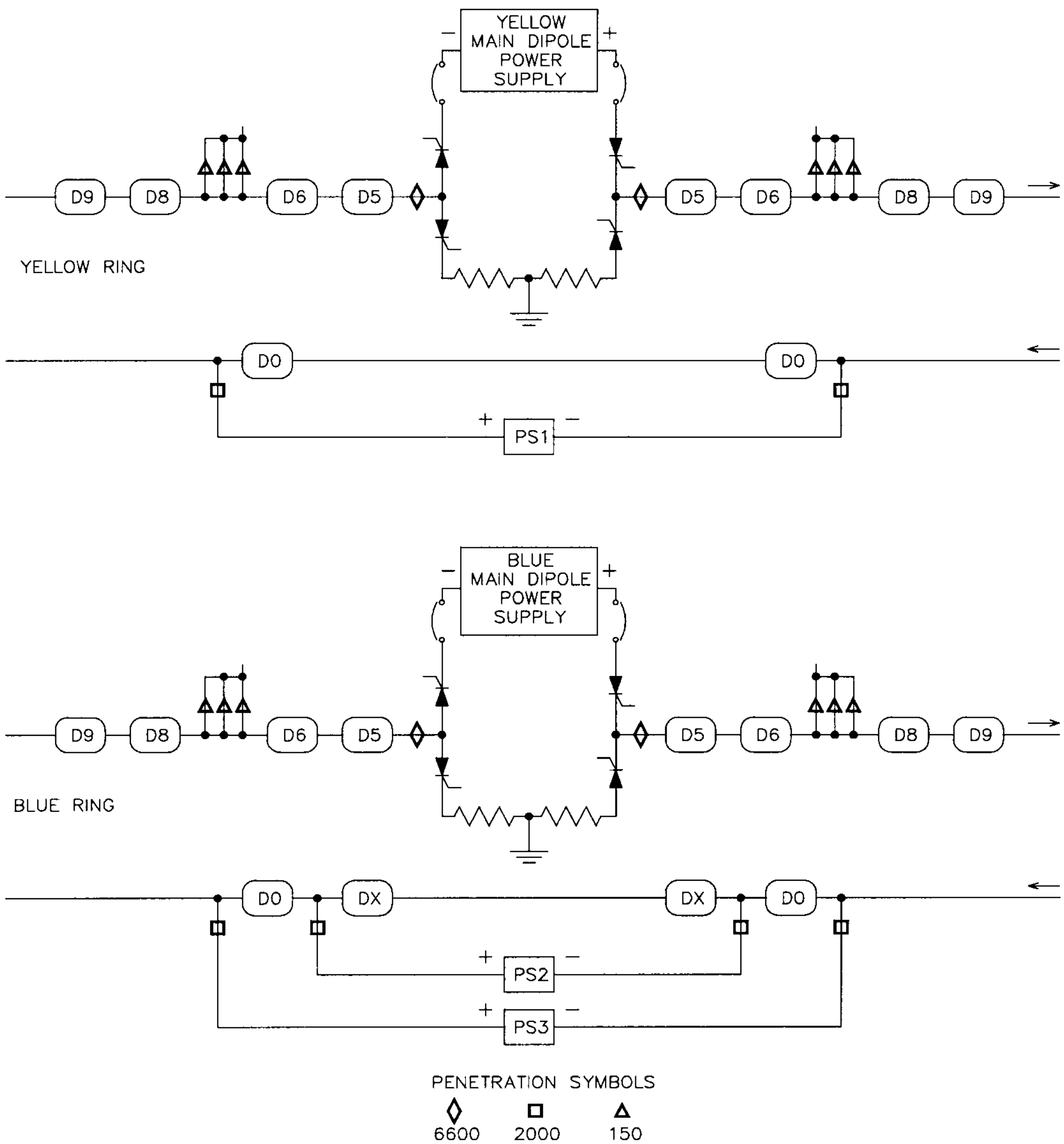


Fig. 1-8. Insertion dipoles at 4 o'clock.

Insertion Quadrupole Power Supplies

The quadrupole insertion schematics are shown in Figs. 1-9 through 1-11. Current flows through the regular Q_V quadrupoles, then through a set of insertion quadrupoles. This pattern repeats until the circuit has gone half way around the ring, then returns through the series connection of the Q_H regular quadrupoles (see Fig. 1-3) and the remaining insertion quadrupoles.

The choice of circuit configuration for the various insertion quadrupoles has been chosen to minimize power supply and current penetration requirements and is sized to allow a continuous change of $ß^*$ between 1 and 10 m. This is implemented in two ways. The current in some of the insertion quadrupoles is varied with shunt supplies. But, in CQT4, 5 and 6, trim quadrupoles are added where the sextupoles are located in the CQS assemblies. These trim magnets allow tuning the insertions at lower currents. The shunt supply at CQT6 is fixed during the $ß^*$ change.

The inner and outer quadrupole currents at Q6, 7 and 9 are close enough that they can share a single power supply that bridges the crossing point. This is not possible at 10:00, or at 4:00 for Q6 and Q7.

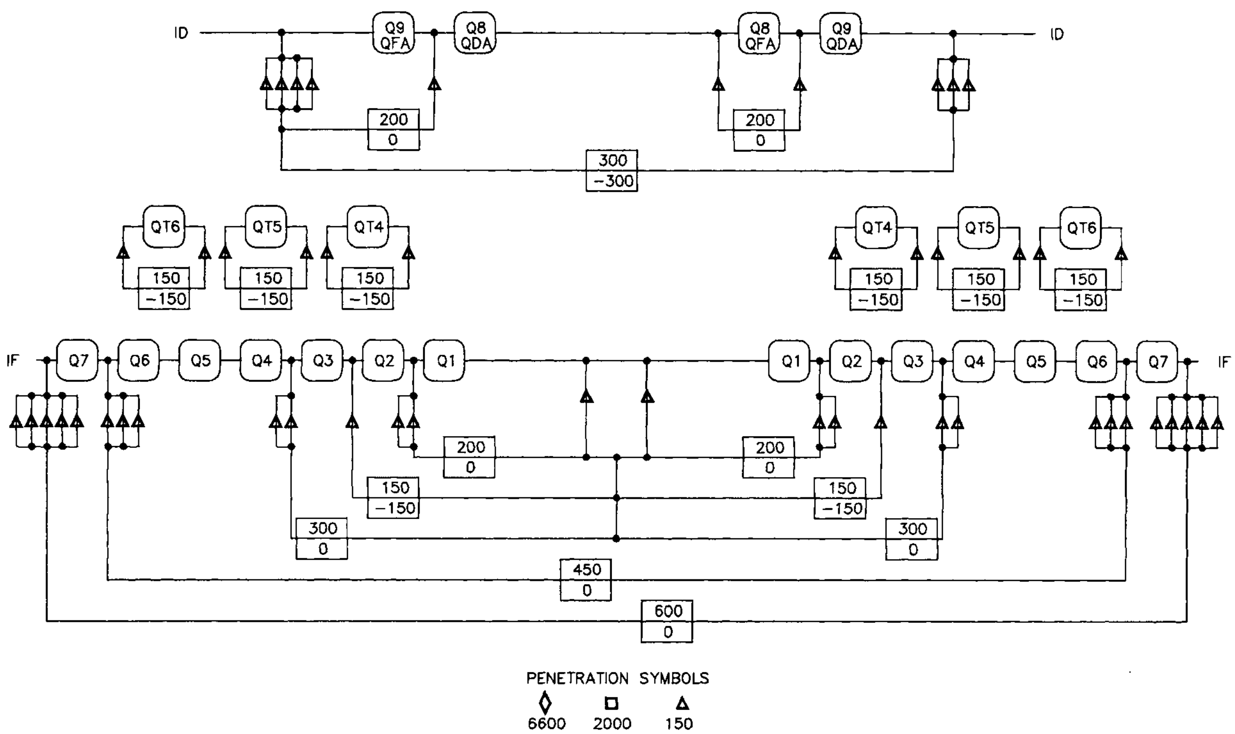


Fig. 1-9. Insertion quads at 2, 6, 8 and 12 o'clock.

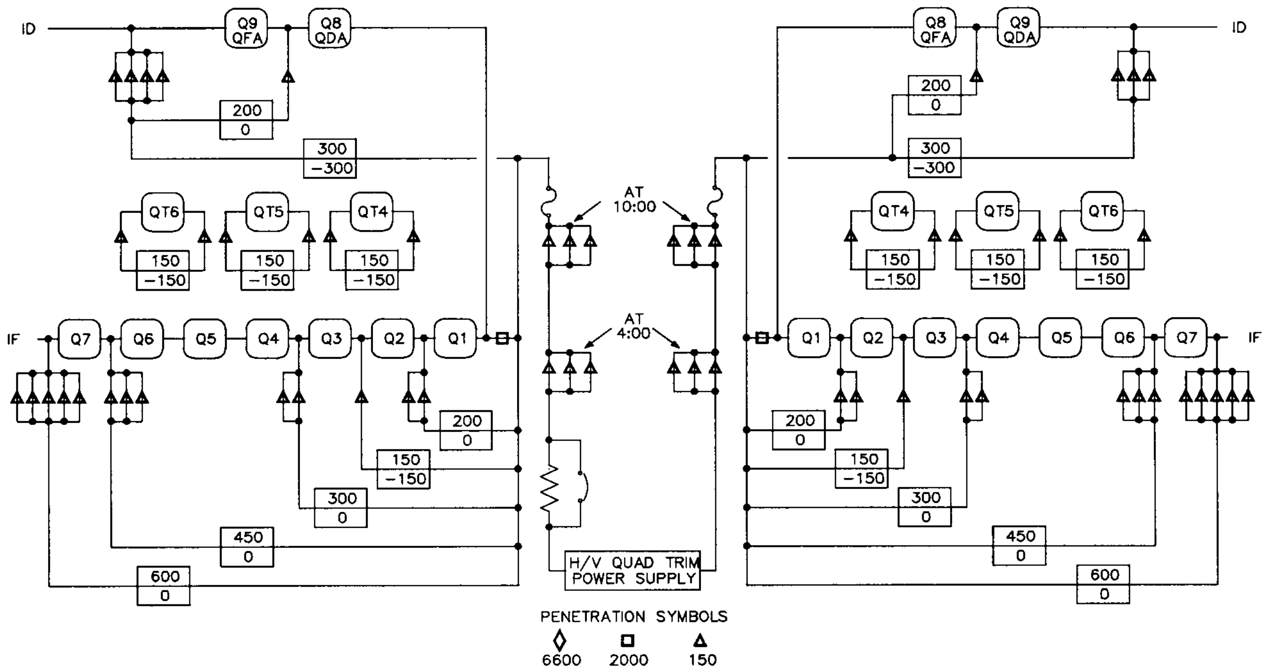


Fig. 1-10. Insertion quads at 10 o'clock.

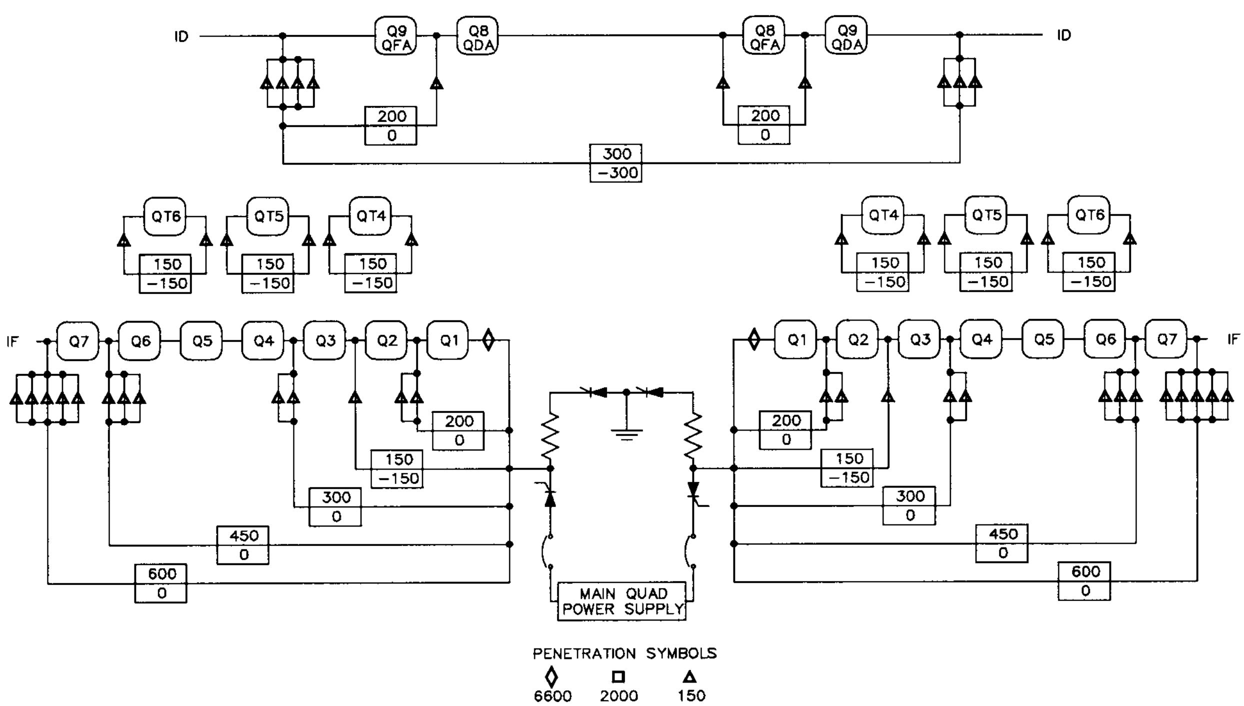


Fig. 1-11. Insertion quads at 4 o'clock.

Correction Magnet Power Supply Systems

There are corrector magnets in each CQ, CQS, or CQT assembly. The leads for these magnets are brought out individually at each CQ- cryostat. If a corrector magnet should fail, this would make isolating the defective magnet possible.

Figure 1-12 shows the circuit scheme for powering the chromaticity sextupoles, b_2. The circuits are symmetrical about the labeled crossing points. These elements are connected in two families, focussing and defocussing, in each arc. Each family is powered individually.

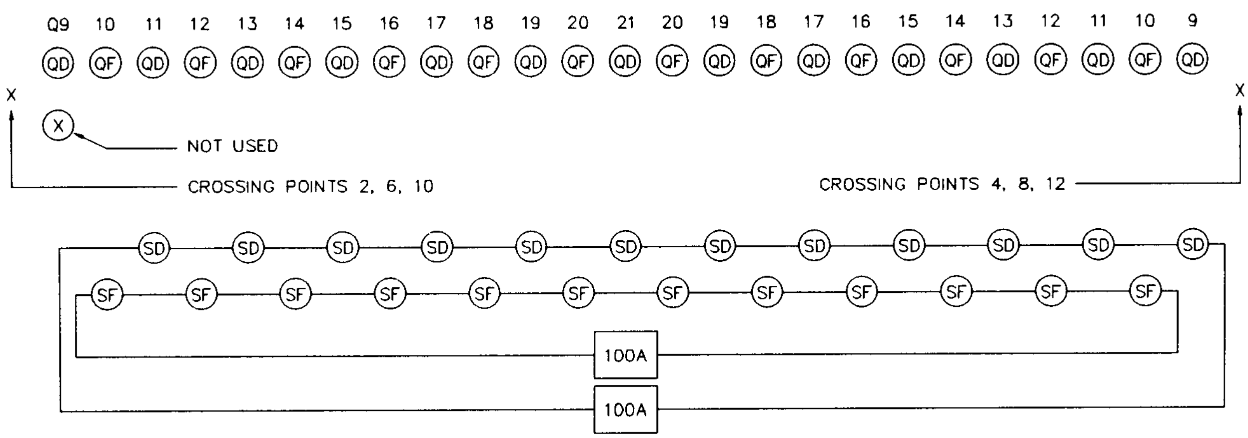


Fig. 1-12. Sextupole circuit.

Figures 1-13 and 1-14 show the configuration of the corrector power supplies for the blue ring. The yellow ring correctors are a mirror image, about the 6:00 insertion region, of the blue correctors. The figures show the correctors in the range, Q10-Q1-Q1-Q18. All the corrector packages in this region are four layers. Outside this range, Q19-Q21-Q10, all corrector packages are single layer (dipole only).

The a_O/b_O closed orbit correction magnets are individually powered in both the arcs and the insertion regions. All are nominally 25 A bipolar supplies, but extra regulators will be available at each alcove to upgrade the current capability to 50 A for up to 25% of the regulators.

The dipole and a_1 correctors in the triplet region are individually powered at every insertion region, in the same manner as the other a_0/b_0 elements. In addition, at those regions requiring the lowest β^*, the b_2, b_3, b_4, and b_5 elements are also individually powered. This is indicated in Figs. 1-13 and 1-14 by drawing those elements within a dotted circle. In its initial configuration, low β^*

will be required at the 6:00 and 8:00 regions, but as the leads to all the correctors are available, the other insertion regions can easily be upgraded.

The other corrector supplies are connected as shown. Where circles are shaded, the magnets are not powered, but the leads are available for future use.

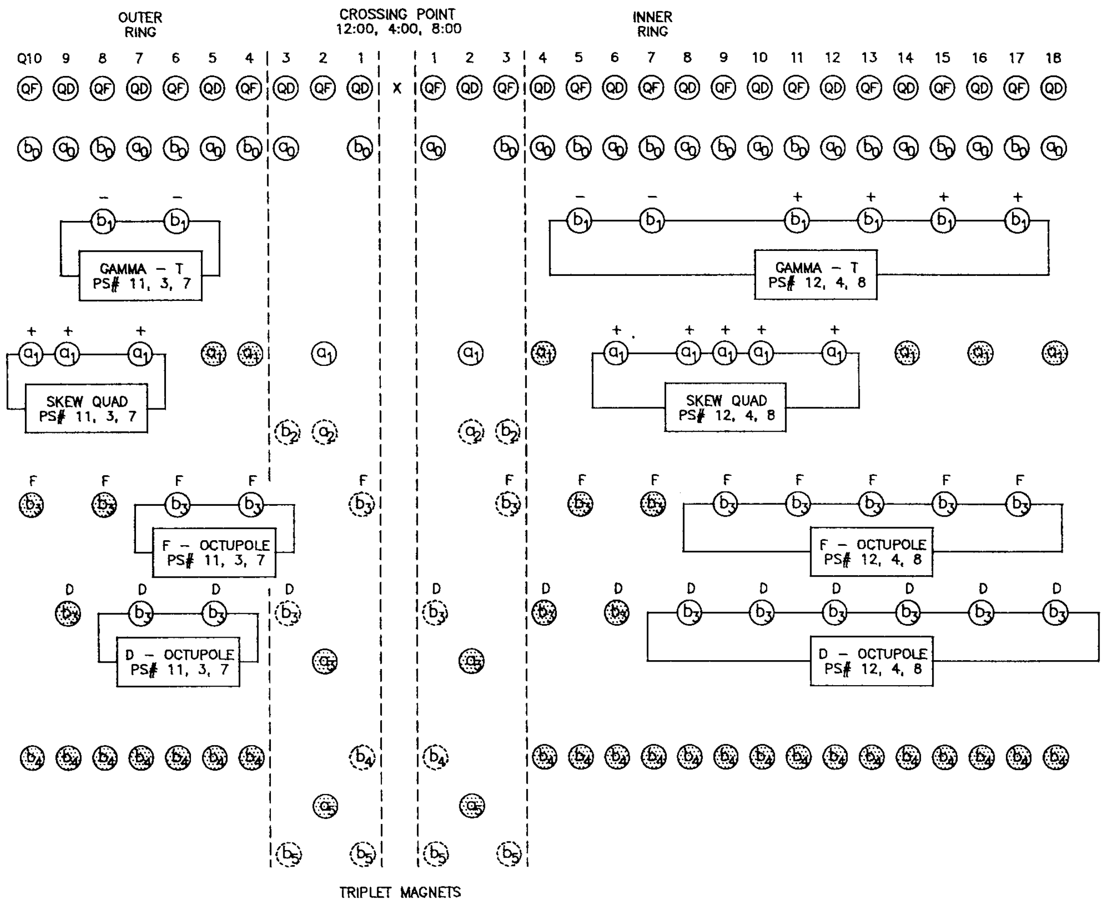


Fig. 1-13. Corrector power supplies at 12, 4 and 8 o'clock.

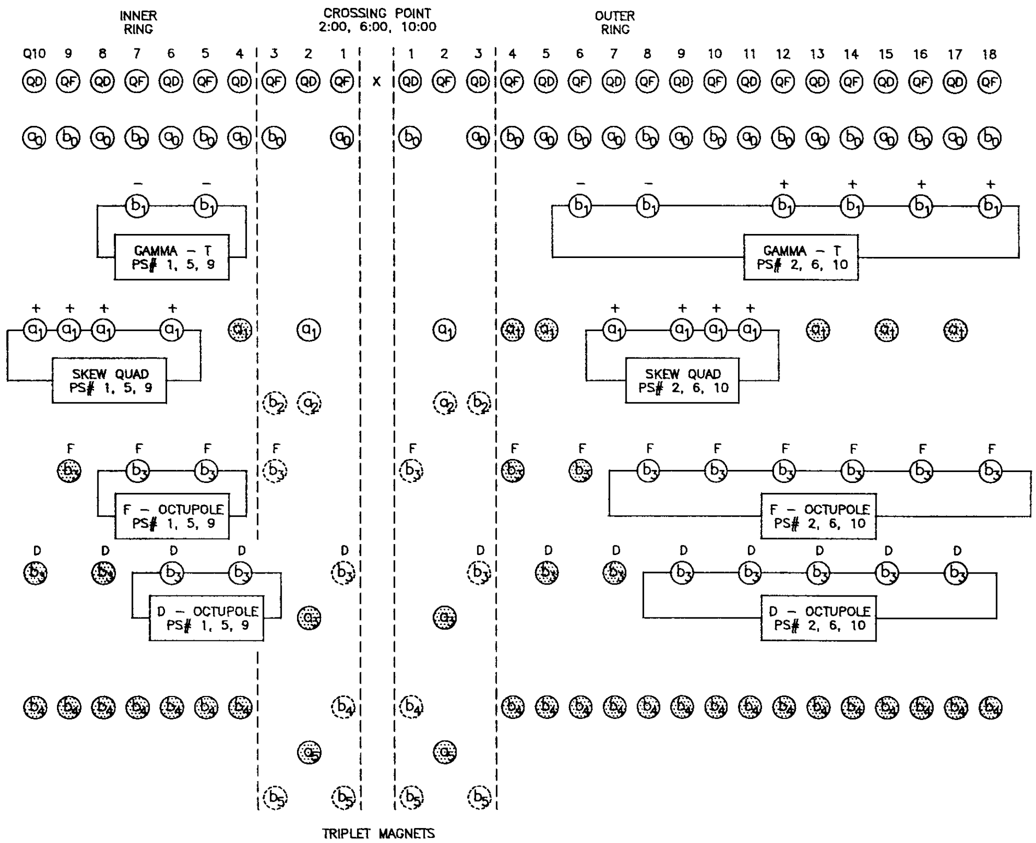


Fig. 1-14. Corrector supplies at 2, 6 and 10 o'clock.

Power Supply Connections of Corrector Magnets

Magnetic Measurement Convention

All magnets were measured and the magnetic field information was recorded according to an “intrinsic” convention, which can be summarized as follows:

All measurements are made from the lead end. When looking into the magnet from the lead end of the magnet, the positive x-axis points to the right hand side, while the positive y-axis points upwards. The origin is chosen to be at the center of the magnet.

In a nominally single-harmonic magnet, the magnetic field, generated by a positive current into the positive pin, is fully defined by its strength and direction on the right (positive-x) half of the median plan. Here, all normal magnets have a pure positive B_y (pointing upward), and all skew magnets have a pure positive B_x (pointing to the right) field component.

The power supply is connected to the magnet at a terminal, to which the wire pair is brought and numbered so that the positive pin has always the larger number. For example, the 8-cm corrector magnets in the CQS (corrector-quadrupole-sextupole) unit are powered during magnetic measurements as follows:

Dipole, horiz and vert	#12 positive, #11 negative
Quadrupole, normal and skew	#10 positive, # 9 negative
Octupole	#8 positive, # 7 negative
Decapole	#6 positive, # 5 negative
Sextupole magnet	#4 positive, # 3 negative

The 13-cm correctors in the triplet are powered during magnetic measurements as follows:

Dipole, horiz and vert	#12 positive, #11 negative
Sextupole, b2	#8 positive, # 7 negative
Octupole, b3	#10 positive, # 9 negative
Decapole, b4	#8 positive, # 7 negative
Dodecapole, b5	#6 positive, # 5 negative
Skew quadrupole, a1	#8 positive, # 7 negative
Skew sextupole, a2	#4 positive, #3 negative
Skew octupole, a3	#6 positive, #5 negative
Skew dodecapole, a5	#2 positive, #1 negative

Optical Properties of Magnets

In addition on the direction of the exciting current, the “functional” or optical properties of a magnet; i.e, its effect on the beam, will depend on the ring into which it is installed and on its direction with respect to the beam in that ring. For RHIC, the convention defining the “installed” direction of the main dipole and quadrupole magnets in both rings refers to the blue ring, in which the beam travels clockwise (CW).

Extending this convention to corrector magnets has the ring-wide consequence that a clockwise installation in the blue ring implies that the beam enters the non-lead end, whereas in the yellow ring clockwise installation implies beam entering the lead end of any magnet.

All arc dipoles are CW installed.

The installation of the arc quadrupole magnets depends on the sector location as follows:

Sector 2, 3, 6, 7, 10 and 11 is CW

Sector 1, 4, 5, 8, 9 and 12 is CCW

Dipole corrector, sextupole, and trim quadrupole magnets are attached to a main quadrupole and the installation of the combined unit follows the rule for the main quadrupole. Depending on the mechanical arrangement of the magnets within the unit, the attached magnet can be clockwise (CW) or counter-clockwise (CCW). The clockwise unit has the attached magnets installed as

in CW-CQS : Corrector CW, sextupole CCW

in CW-CQT: Corrector CW, trim magnet CCW

in CW-Q2: Corrector 1 (style I, J) CCW

in CW-Q3: Corrector 2 (style K) CW, corrector 3 (style L,M) CCW

In the triplets, the lead end of Q1 and Q2 is on both sides away from the IP and in Q3 towards the IP.

Prescriptions for the Power Supply Connections

In order to bring the above rules into conformance with the MAD convention used in the RHIC model, the power supply connection of the magnets in the ring will, in some cases, require polarity changes from those used for the magnetic measurements to accommodate the specific ring location and the installed direction of the magnets. The corrector power supply connections have to be done according to the prescriptions of the attached Table 1-5.

Table 1-5. Corrector Power Supply Connections

Positive:	Connected as for magnetic measurements
Reverse:	Connections reversed from magnetic measurements
CW Installation:	Beam enters **non-lead end** in BLUE, **lead end** in YELLOW
CCW Installation:	Beam enters **non-lead end** in YELLOW, **lead end** in BLUE

BLUE		**YELLOW**
	b1 (quad), b3 (oct), b5 (dodec)	
CW: Positive		CW: Reverse
CCW: Reverse		CCW: Positive

b2 (sext), b4 (dec)	
CW: Positive	CW: Reverse
CCW: Positive	CCW: Reverse
Skew a1 (quad), a3 (oct), a5 (dodec)	
CW: Reverse	CW: Positive
CCW: Reverse	CCW: Positive
Skew a2 (sext)	
CW: Reverse	CW: Positive
CCW: Positive	CCW: Reverse

Main Magnet Power Supplies

Overview

The RHIC Main Magnet Power Supplies (RMMPS) provide the current for the main dipole and main quad magnet strings. The main dipole and main quad magnet strings are separate electrical circuits; since there is a separate RMMPS for each circuit, and each ring, there are four RMMPS.

Each RMMPS has three major components, the Flat-top Power Module (FTPM), the Ramp Power Module (RPM), and the Output Circuit Compartment (OCC). The power modules supply the current to the magnet strings. The OCC houses the output filter, the quench protection components, the regulator and remote PLC monitoring. Figure 1-15 shows the main power supply block diagram and the interconnection of these sub-systems. Each of these sub-systems is described in a section below.

Sub-System Descriptions

Power Modules

There are two power modules for each RMMPS. Each power supply has one FTPM and one RPM connected in parallel. The two power modules for each RMMPS are 12-pulse, phase controlled power converters. Only one of these power modules is active at a given moment. The regulator selects the active power module based on the instantaneous current slope. When the current slope is low the FTPM is active. During a ramp, when the current slope is above a selected level, the RPM is active. This allows the power modules to be sized for the voltage necessary to maintain the required current slope. This approach provides low voltage ripple when the current is a constant value. The only major difference between the different types of power modules are the rectifier transformers. The RPM transformers are not sized for continuous operation. The voltage and current ratings of the modules are listed in table 1-6.

Table 1-6
Ratings of Power Modules

POWER MODULE TYPE	VOLTAGE RATING	CURRENT RATING	POWER RATING
Quad Flat-top	15 V	5500 A	82.5 kW
Quad Ramp	90 V	5500 A pk 3300 A rms	495 kW pk 297 kW
Dipole Flat-top	30 V	5500 A	165 kW
Dipole Ramp	400 V	5500 A pk 3300 A rms	2200 kW pk 1320 kW

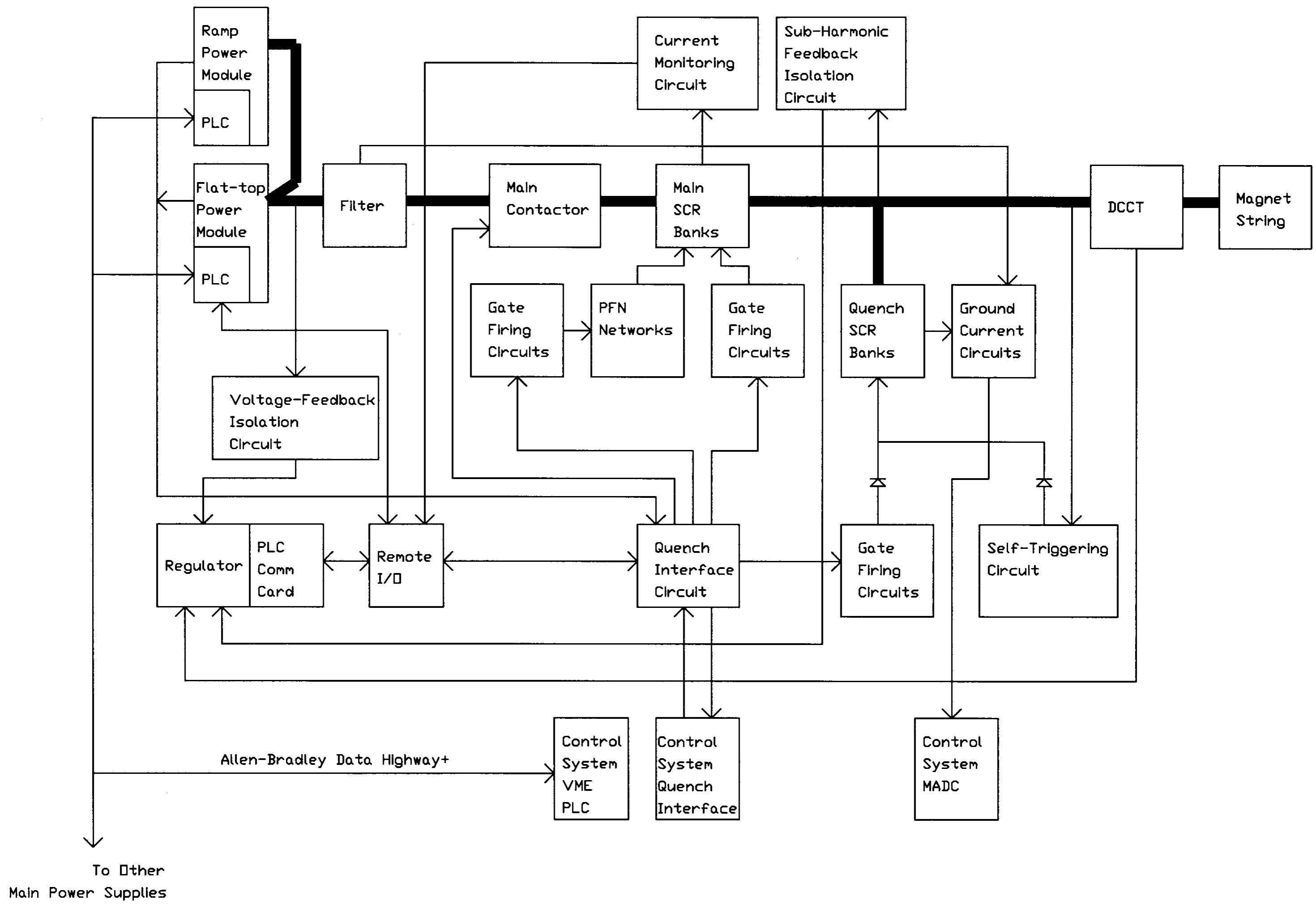


FIGURE 1-15

MAIN POWER CIRCUIT BLOCK DIAGRAM

Regulator

The regulators for the RMMPSs are digitally based using the TI320C30 Digital Signal Processor (DSP) as the computation engine. Figure 1-16 shows the overall configuration of the regulator. As indicated in the diagram one regulator controls two power modules.

The regulator has a Phase Locked Loop (PLL) that is locked to the power line. This PLL provides all the timing signals for the regulator. The DSP receives voltage, current, and sub-harmonic feedback through A/Ds that sample these parameters at 11520 Hz. The DSP uses this feedback and calculates a command count that is written to the digital firing cards. The digital firing cards use this command count to develop firing signals for the power module's SCRs. The SCR firing signals are sent to the power module's SCR gating circuits over fiber optic cables. There is a separate digital firing card for each power module attached to the regulator. The active power module is selected by enabling the output of its' digital firing card.

The current command, and the readbacks for the Real Time Data Link (RTDL), are exchanged over a fiber optic link between the waveform generator, in the control system chassis, and the Serial I/O Card in the regulators. This data is exchanged at 720 Hz. The regulator also communicates with a PLC through a PLC communications card. This card provides digital input and output that is used to control the regulator, and return status, through the control system. There is also a fiber optic lick to the RMMPS control computer. This computer provides program maintenance and diagnostic capabilities.

To insure the stability of the analog feedback circuits the regulator is housed in a temperature controlled enclosure. This enclosure uses thermoelectric modules that provide a temperature stability of +/- 0.2 °C.

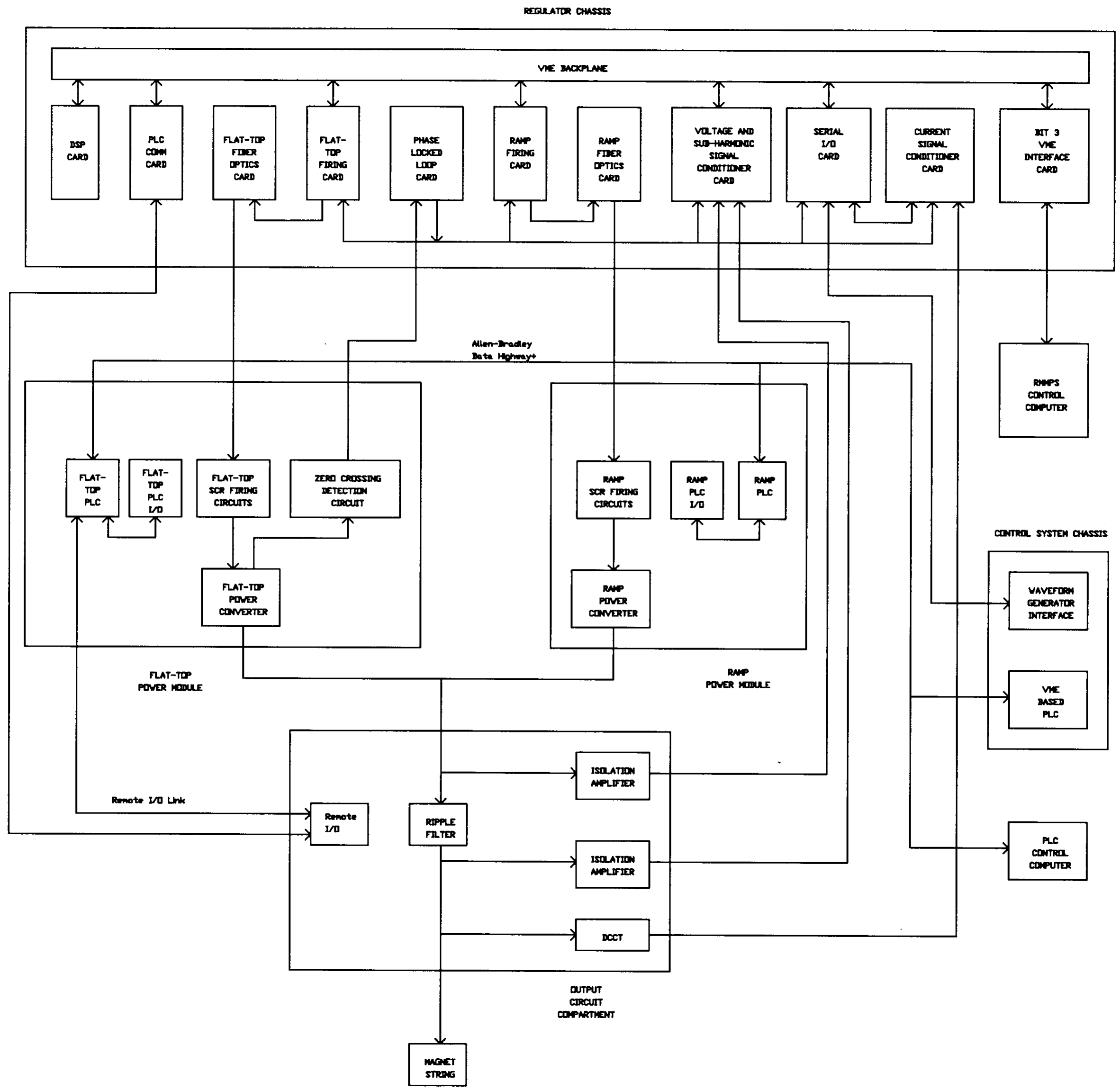
The regulator sends analog readbacks to the control system's Multiplexed Analog to Digital Converter (MADC) system. These signals are used for diagnostics and are stored when the quench link goes down. The readbacks for the RMMPS are: reference setpoint, actual current, output voltage, current error, power supply ground current, quench ground current, flat-top power module output current, and the ramp power module output current.

Output Filter

The output filter reduces the current ripple in the magnet string by reducing the voltage ripple at the power module's commutation frequency of 720 Hz. The voltage reduction at 720 Hz is approximately 15 dB.

The output filter is a three pole passive RLC filter with a corner frequency of 90 Hz. This corner frequency insures that the filter's peaking is not at 60 Hz, or its harmonics.

FIGURE 1-16 REGULATOR BLOCK DIAGRAM



Quench Protection and Main Magnet Power Supply System

The quench protection system extracts the stored energy in the main magnet strings. The major system blocks are shown in Figure 1-17 and are labeled: DC Contactor, Main SCR Firing Circuits, Pulse Forming Networks, and the Quench Control Interface.

The quench link signal, originating in the Control System Quench Interface, is an input to the Quench Control Interface Circuit in the OCC. This signal is a TTL high level during normal operation, it goes low to initiate the energy extraction. When this event occurs the Quench Control Interface Circuit (QCIC) immediately turns off the gate drive to the Main SCR Firing Circuits and triggers the Pulse Forming Network (PFN) attached to the Main SCRs. The PFN shuts off the Main SCRs, this action isolates the RMMPS from the magnet string. The QCIC then fires the Quench SCRs, and the magnet current is now diverted into stainless-steel resistors that extract the energy. The QCIC then opens the Main Contactor, which provides a mechanical backup to isolate the power supplies from the magnet string in the event the Main SCRs fail to open. The QCIC then turns the power modules off. If the QCIC or the Gate Firing Circuits attached to the Quench SCR Banks fail to trigger the Quench SCRs, the resultant voltage rise will trigger the Self-Triggering Circuit. This circuit provides a backup for the QCIC and will fire the Quench SCRs independently.

PLC System

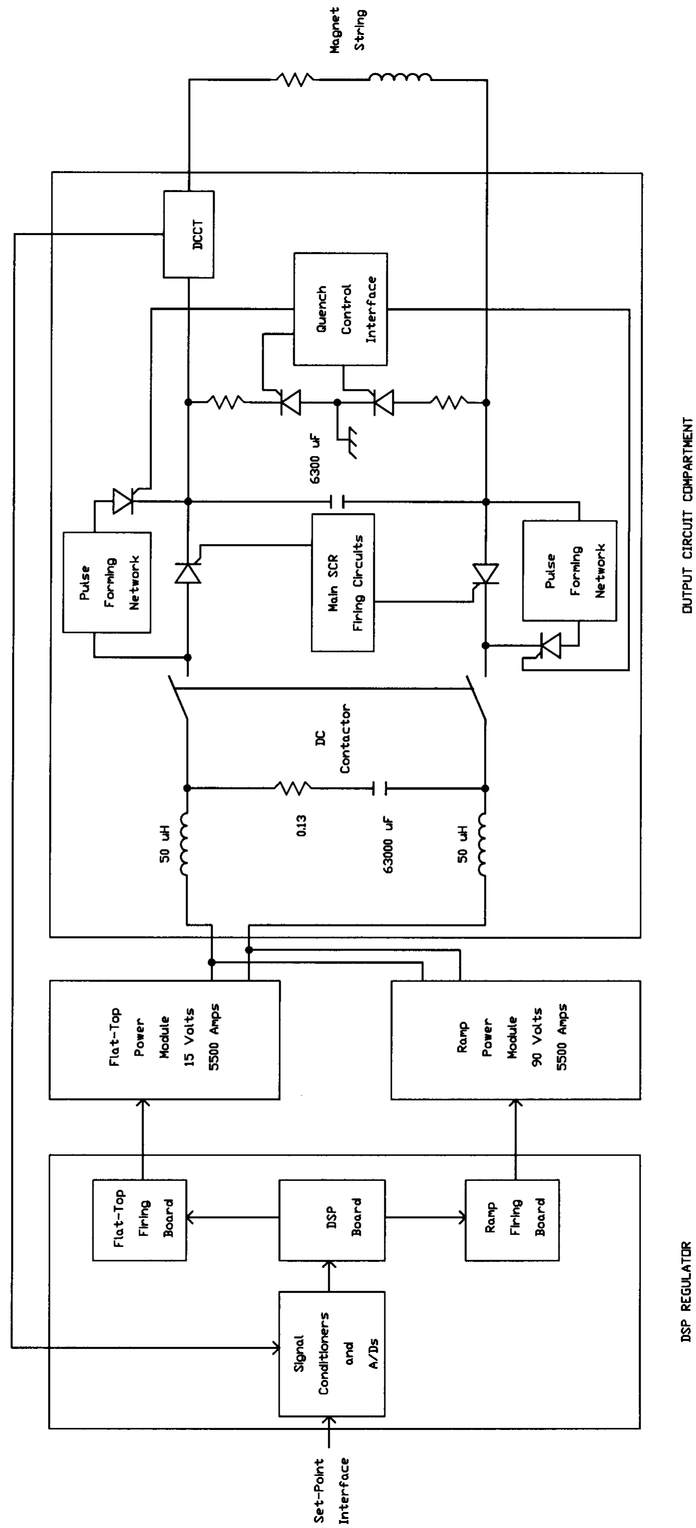
The PLC system provides status reporting, state control, and local protection of the RMMPS. Each power module contains an Allen-Bradley PLC-5/25. These PLCs are connected to an Allen-Bradley PLC-V5/40, which resides in the Control System Chassis, via the Allen-Bradley Data Highway + serial link. The FTPM PLCs are also connected to remote I/O in the OCCs. These connections tie all the regulators and all the power modules to the control system and provide the status reporting and state control functions.

The PLC-V5/40 collects the status from the power module PLCs and stores this information in dual-port RAM that is accessible to the control system's Front End Computer (FEC), which resides in the same chassis. The FEC can also write commands to this RAM. The PLC-V5/40 contains ladder logic that receives these commands from the control system, and then coordinates turning the power supplies on or off.

The PLC in each power module contains ladder logic that monitors various parameters in that power module. If a failure condition is detected the PLC opens the Master Interlock Relay (MIR) in the power module. Opening the MIR causes the power module to shut down and the power supply fail signal to be sent to the control system. This brings down the quench link signal which activates the quench sequence described above, providing an orderly shut-down of the RMMPS.

The Allen-Bradley Data Highway + also connects to a PLC control computer. This provides PLC ladder logic maintenance capabilities.

FIGURE 1-17 MAIN POWER SUPPLY
BLOCK DIAGRAM



Insertion Power Supplies

The insertion power supplies - These include the shunts to the insertion dipoles, D0 and DX, the shunts to the insertion quadrupoles, Q1-3, and Q6-9 and the trim quadrupole supplies at CQT4, 5, and 6. They were specified in modular sizes to minimize the quantity of types of supplies to maintain, and to simplify procurement. All of the insertion power supplies are located in the service buildings. The types and quantities of IR power supplies are listed in Table 1-7.

Table 1-7. Power Supply Summary

Item	Polarity	Voltage (V)	Current (A)	Quantity (2 rings)
Main Power Supplies				
Quad H/V Trim	mono	40	300	2
Insertion Dipoles				
Type A	mono	20	2000	14
Type B	mono	20	600	7
Insertion Quadrupoles				
Type A	bi	15	150	96
Type B	bi	15	300	14
Type C	mono	15	200	48
Type D	mono	15	300	24
Type E	mono	15	450	16
Type F	mono	20	600	16

Monopolar Insertion Power Supplies

The monopolar insertion power supplies are current regulated DC power supplies with an inner voltage loop. The AC input to these power supplies is 3 Phase 480VAC for the 2000A and 600A units. The AC input to the rest of the lower current units is 3 phase 208VAC. All of the monopolar power supplies utilize a 12 pulse SCR bridge Power Converter with an output LCRC filter. The current sensing element for current feedback to the current regulator is a DCCT. The required reproducibility is 0.01% of the maximum output current. All of these power supplies have a 100% and 50% voltage tap setting.

Bipolar Insertion Power Supplies

The Bipolar insertion power supplies are also current regulated DC power supplies with an inner voltage loop. However, the bipolar supplies utilize a switchmode DC-DC converter which is controlled by a tracking voltage loop. This tracking voltage loop is in addition to the power supply voltage loop. The DC-DC Converter is a Pre-Regulator for a MOSFET Output Power stage. The voltage across the MOSFET Output power stage is fed back to this tracking voltage loop which keeps the voltage across the MOSFET Power stage low so as to reduce power dissipation across these MOSFETS. The MOSFET Output power stage is an H-bridge configuration. Two of the MOSFETS act linearly while the other two MOSFETS act like a switch controlling which direction the current flows through the magnet load. The number of MOSFETS in the Output Stage of the bipolar 150A power supplies is 24 and the number of MOSFETS in the Output Stage of the bipolar 300A power supplies is 48. The input to these power supplies is 3 phase 208VAC.

Nesting of Monopolar and Bipolar Insertion Power Supply Systems

In any sextant of RHIC there can be as many as 7 power supplies nested inside one power supply. Due to this nesting, all of the insertion power supplies must float off of ground. The DC Output terminals of the 2000A and 600A power supplies have been put through high potential testing of 2500VDC because they are on the Dipole Circuit which has a much higher inductance than the quadrupole circuit. For this reason the 2000A and 600A power supplies will float off of ground to a higher voltage. The lower current units have been put through high potential testing of 1600VDC because they are on the quadrupole circuit which floats off of ground to a voltage which is lower than the dipole circuit.

The nesting of the insertion power supplies and the use of superconducting magnets also created complex time constants which made it very difficult to stabilize the current loops of these power supplies. In some cases the measured admittance of the load was not a pure inductance but also had some capacitive components.

Insertion Power Supply Control System

All of the insertion power supplies use the same 3u chassis control bucket. In this control bucket resides the fiber optic interface card, the current regulator card, the buffer card, the DCCT electronics card, the voltage regulator card, the digital isolation card and the control card. The fiber optic interface card receives the power supply current setpoint over fiber and converts it to an analog current setpoint utilizing a 16bit D/A. This analog setpoint is sent over the 3u control chassis backplane to the BNL designed current regulator card. This current regulator card has a removable PC board for adjusting time constants to stabilize the power supply current loop. The buffer card sends four analog signals back to the Multiplexed Analog to Digital Converter (MADC). These four signals are power supply current setpoint, output current, output voltage and power supply current error. The DCCT electronics card and voltage regulator card were purchased from an outside vendor. The voltage regulator card also contains the isolated shunt feedback voltage which is used in the DC overcurrent circuit which is built into the voltage regulator card. The digital isolation card receives commands from a Node card which is external to the power supply and sends power supply statuses back to this Node card. The Node card communicates over a MODBUS Plus network to a MODICON Programmable Logic Controller (PLC). This PLC communicates with the front end VME computer over an Ethernet connection. A NODE card is an inexpensive multichannel I/O device designed at BNL which receives commands from the PLC and distributes these commands out to as many as 12 power supplies. The power supply statuses are also sent back to the NODE card and then onto the PLC from the NODE card. The control card controls which state the power supply is in and monitors the power supply faults and trips the power supply to a fault state if a fault occurs. This control card employs a micro processor to control the power supply.

The insertion power supplies must also interface with the quench protection system. There are connections made to the Quench Protection Assembly (QPA) and the Quench Detector. The power supply sends the power supply status to the QPA and any QPA faults are sent back to the power supply as well. The power supply output current is sent to the Quench Detector.

RHIC BIPOLAR CORRECTOR POWER SUPPLIES

The bipolar 50A corrector power supplies operate on the principles based on the simplified block diagram shown in Fig. 1-18.

The incoming 3 phase 208 VAC, after going through 3-phase rectification and simple LC filtering, is fed into a dc-dc converter. The output of the converter is controlled by a tracking voltage loop, which constantly monitors the difference between the converter output filter voltage and the magnet voltage and make it equal to a voltage set point. What this means is that the converter will track the magnet voltage to keep the voltage drop across the MOSFET output stage constant. 4 MOSFET transistors switching at 100 kHz make up the converter. The four quadrant converter has an H bridge configuration. Output voltage is controlled by pulse width modulation (PWM) technique.

The MOSFET output stage of the power supply consists of 8 transistors and also has an H bridge configuration. Each of the upper MOSFET operates linearly. That is, it regulates the current by acting like a variable resistor. In contrast, each of the lower MOSFET acts like a switch.

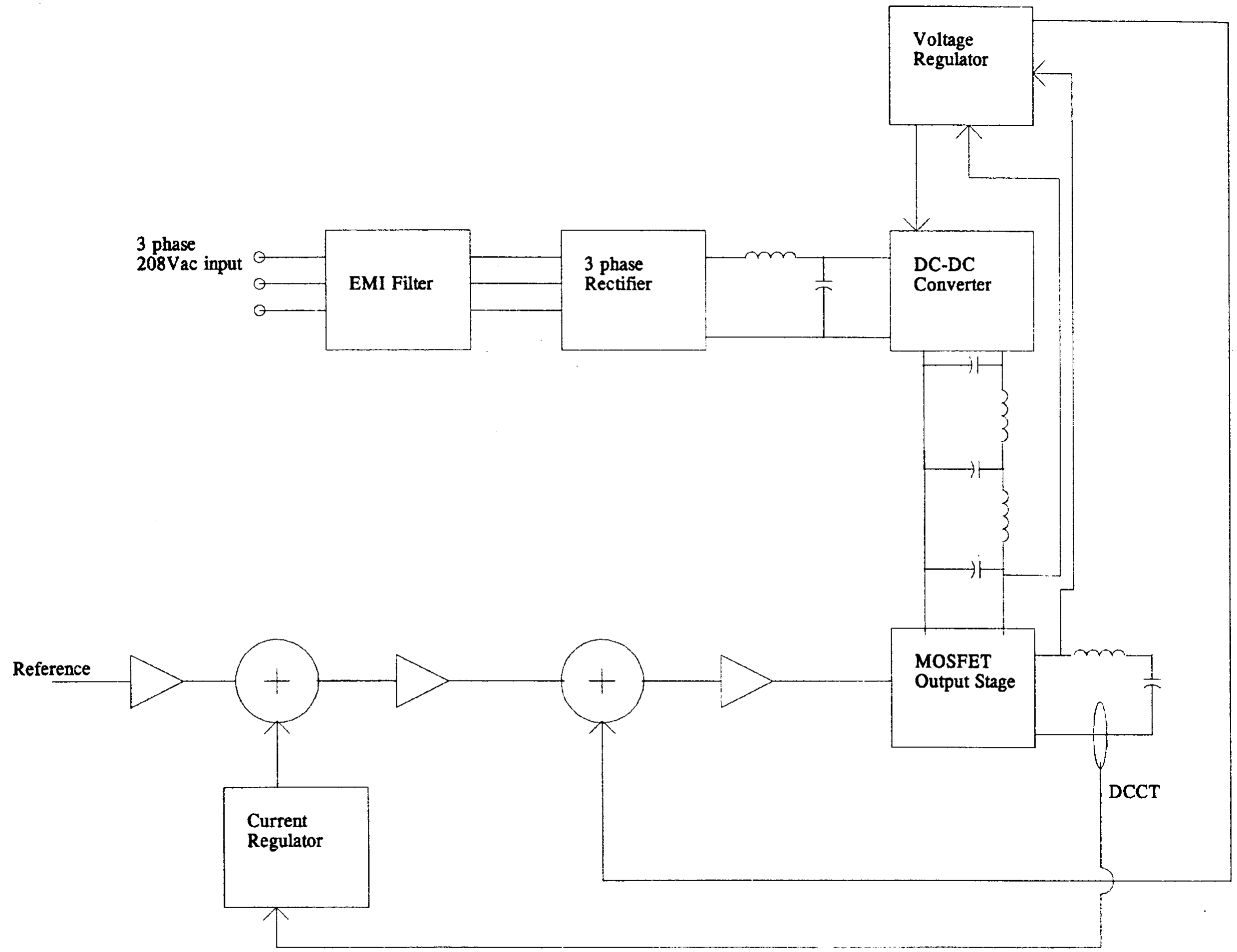
There are basically three types of feedback loops employed in the power supplies: an inner voltage feedback loop, an overall current feedback loop, and a tracking voltage loop. With a resistive load, the current feedback has a frequency response of 4 Hz. Putting the power supply into voltage mode disables the current feedback. In this case, the power supply turns into a voltage regulator and has a frequency response of 1 kHz.

The tracking loop minimizes the output stage power dissipation by keeping the voltage drop across the MOSFET transistors to about a volt. Whenever the tracking loop fails to track the output voltage the power dissipation increases, which can lead possibly to a thermal shutdown. Feedback is taken after the dc-dc converter output filter. The frequency response of the tracking loop is about 3 Hz.

Both voltage and current compensation can be accomplished on an external compensation board, which is mounted onto the power supply control board via an opening in the front panel.

Although the power supplies employ dc-dc converters, they have to meet the following noise specifications: For normal mode ripple, $V_r < 5$mVpp narrow band (20 Hz – 1 kHz) and < 50 mVpp wide band (1 kHz – 1 MHz). For common mode ripple, $V_r < 20$ mVpp narrow band and < 200 mV wide band.

All of the corrector power supplies provide four analog signals SETPOINT, DCCT, OUTPUT VOLTAGE, and ERROR at the front panel for troubleshooting and testing purposes. The first three signals are also available at the rear panel. In LOCAL mode, the set point for the 50A unit can be adjusted on the front panel by turning a knob.



RHIC BIPOLAR POWER SUPPLY SIMPLIFIED BLOCK DIAGRAM

Figure 1-18

SEXTUPOLE POWER SUPPLIES

Power Supplies

There are a total of 24 sextupole power supplies in both rings. All of the sextupole power supplies are located in the alcoves. The sextupole power supplies are current regulated DC power supplies with an inner voltage loop. In addition to this inner voltage loop these sextupole power supplies have a linear MOSFET output stage with a 12 pulse SCR Pre-Regulator. These power supplies use a DCCT as the current sensing element. The required power supply current reproducibility is 0.025% of maximum current rating. The power supply maximum ratings are 100Volts at 100Amps. The AC input is 3 phase 480V at approximately 14 Amps maximum. The maximum voltage ripple is 0.2Vpp in the 100% tap setting. The power supplies have a 70V tap setting as well. The block diagram is shown in Fig. 1-19.

Power Supply Controls

Each power supply receives an analog setpoint from an external fiber optic interface card. This fiber optic interface card receives the setpoint over fiber and converts it to an analog current setpoint utililizing a 16 bit D/A.The OFF, STANDBY and ON Commands to the power supply, as well as the statuses from the power supply, are sent to a NODE CARD which then communicates over a MODBUS PLUS network with a MODICON Programmable Logic Controller (PLC). This MODICON PLC communicates with the VME front end computer over an Ethernet connection. A NODE CARD is an inexpensive multichannel I/O device designed at BNL which receives commands from the PLC and distributes these commands out to as many as 12 power supplies. The power supply statuses are also sent back to the NODE CARD and then onto the PLC from the NODE CARD. There are four analog readbacks which are sent back to the Multiplexed Analog to Digital Converter (MADC). These four signals are Setpoint, Output Current, Output Voltage, and Power Supply Current Error.

Power Supply Magnet Load

Each Sextupole power supply is connected across 12 sextupole magnets. The 12 sextupole magnets are all connected in series. These magnets are connected in two families, focussing and defocussing in each arc. The inductance of each sextupole magnet is about 0.83H. When twelve sextupole magnets are connected in series the total inductance the power supply sees is about 10H. The only resistance the power supply sees is the warm DC cables to each of the sextupole magnets. This resistance is approximately 0.42 ohms.

Sextupole Power Supply Block Diagram

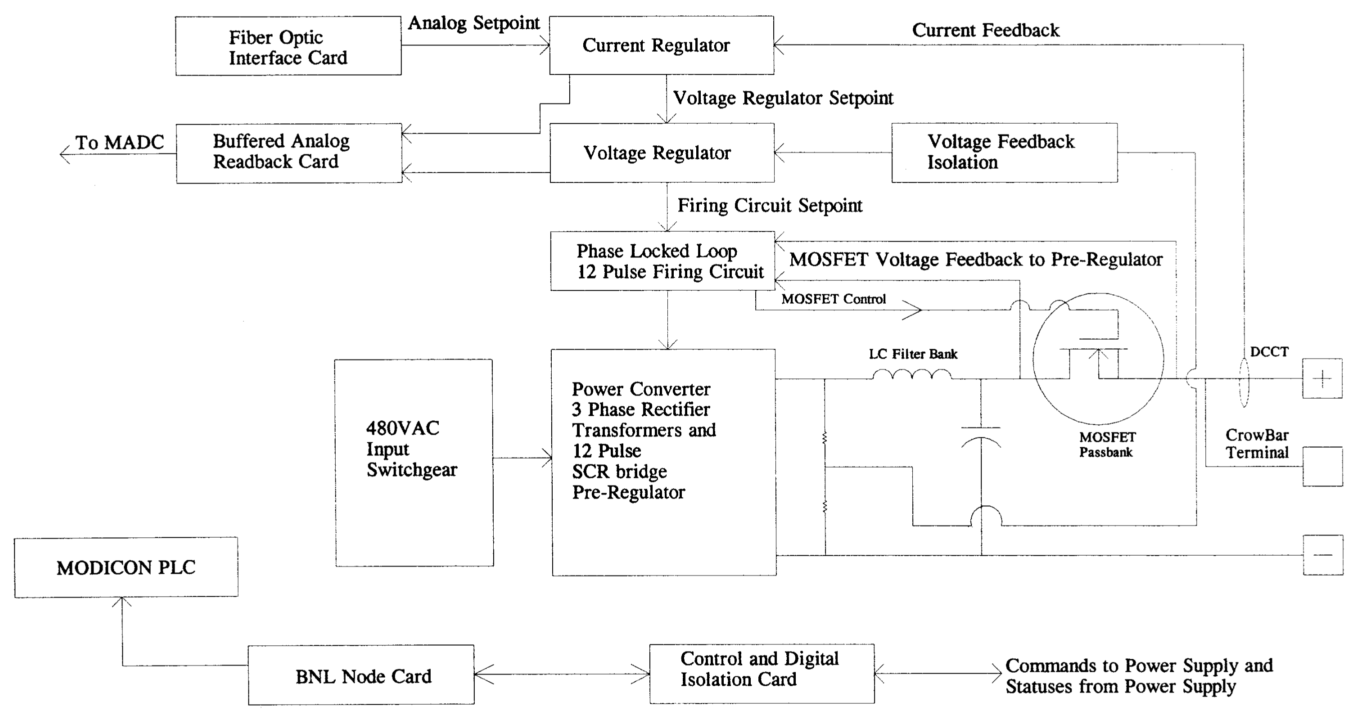


Figure 1-19

Siberian Snake Power Supplies

There are a total of 24 snake power supplies in both rings. All of the snake power supplies are located in the alcoves. Each power supply is rated at a maximum of 15Volts at 440Amps DC. The snake power supplies are current regulated switchmode power supplies with a DCCT current sensing element. The switchmode power section is a commercially available voltage regulated power supply, which is inside a BNL designed current regulator.

The snake power supply receives an analog setpoint from an external Fiber optic interface card. This fiber optic interface card receives the setpoint over fiber and converts it to an analog current setpoint utililizing a 12 bit D/A.

The snake power supply must also interface with the quench protection system. There are connections made to the Quench Protection Assembly (QPA) and the Quench Detector. The power supply sends the power supply status to the QPA and any QPA faults are sent back to the power supply as well. The power supply output current is sent to the Quench Detector. Figure 1-20 is a block diagram of the snake power supply.

Two snake power supplies are required to power one snake magnet. Each power supply powers 2 coils that are in series in each magnet.

Snake Power Supply Block Diagram

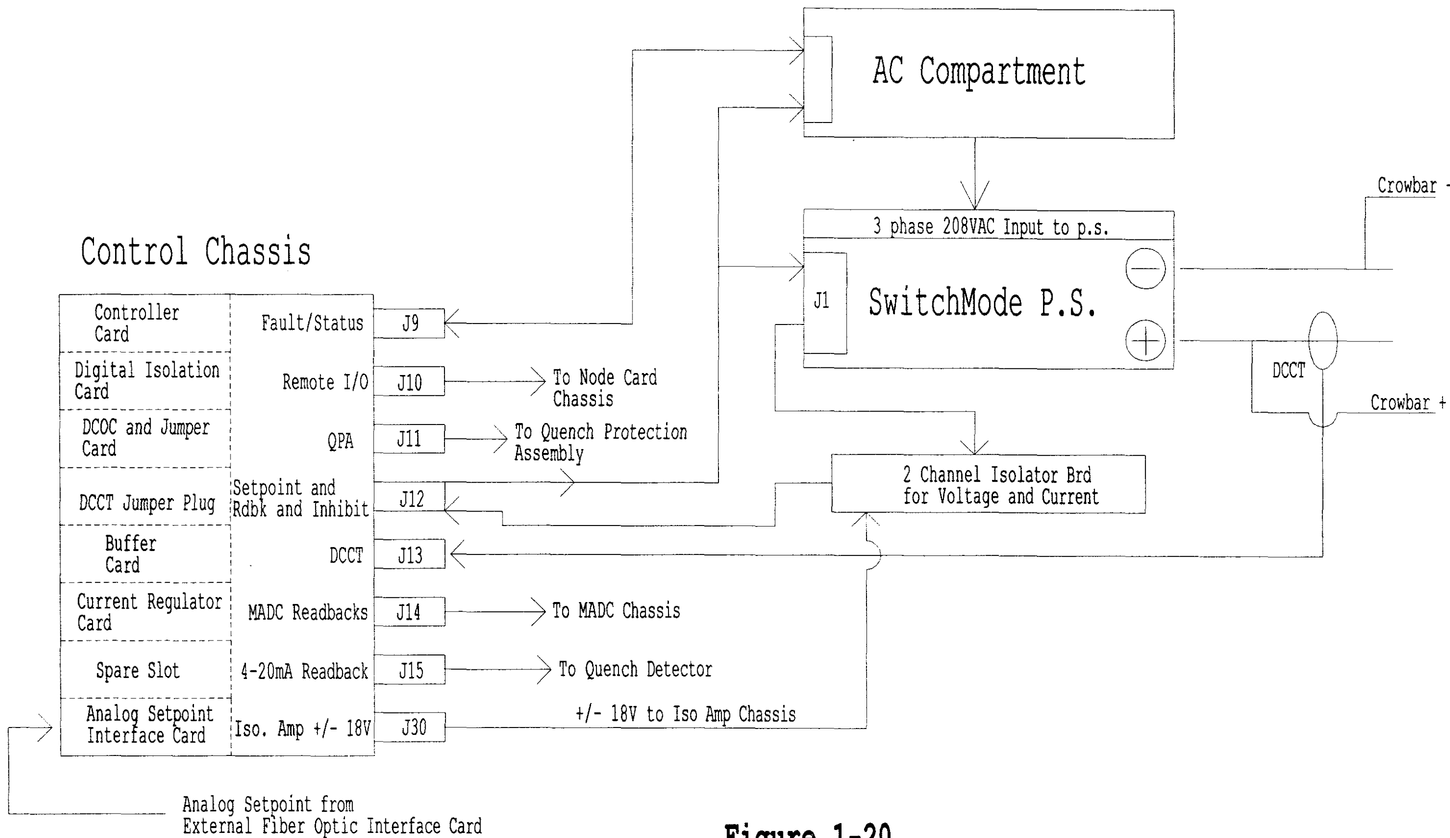


Figure 1-20

Quench Protection System

The quench protection system is used to prevent damage to the superconducting cable or wire used in magnets or bus work. This damage will occur when there is sufficient energy deposited at the initial quenching location to cause the location to rise its temperature above safe operating limits. The current in the quenching magnet or bus must be reduced to zero before overheating occurs. They are three parts to this system. First, the cold bypass diodes are used to divert the current from the non-quenching magnets around the quenching magnet. If the Second, the quench detection system is used to determine when magnet or bus has quenched. The quench detection system will be used to trigger the energy extraction system. Third, the energy extraction system brings the current to zero in the quenching magnets and superconducting buses. This is mainly accomplished by switching in dump resistors in series with the magnet circuits.

Cold Bypass Diode System

Almost all of the collider main magnets are able to absorb their own energy during a quench. With these magnets a passive cold bypass diode system is used to prevent damage to the quenching magnet from current in the rest of the magnet circuit.

The cold bypass diode system is shown in Fig.1-21. In this circuit, the current is forced out of the magnet and into the shunting diode by the natural action of the quench developed resistance of the magnet coil. Current from the non-quenching magnets will not heat the quenching magnet because of the shunting action of the diode. During current ramping the diode must not shunt any significant current.

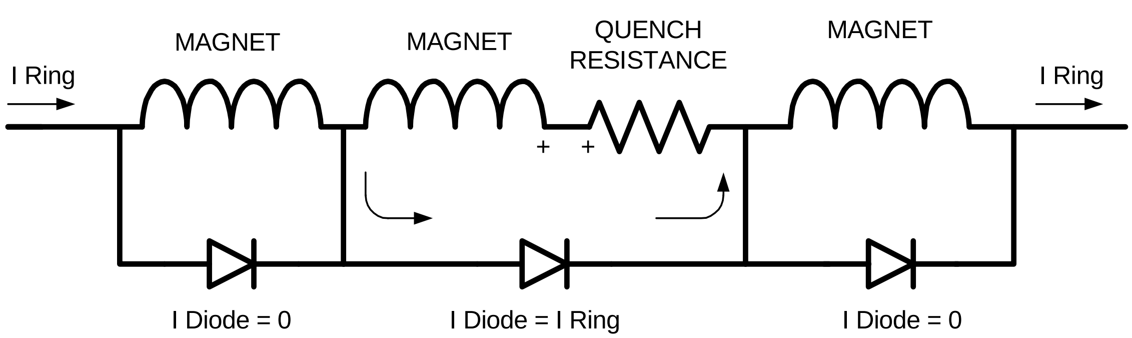


Figure 1-21 Simplified Circuit of a Quench Protection Diode Bypassing Current During A Magnet Quench.

The cold diode assemblies (See Fig.1-22) have two 5 pound copper anvils compressing the diode element. A stainless-steel frame using disc spring washers maintain the large compressive force on the diode element under all operating conditions. This large force is needed for a good electrical and thermal contact between the diode element and copper anvils. Ceramic balls by used to provide electrical isolation between the copper anvils in a stainless-steel frame. The diode lements where specifically passivated for cryogenic temperatures. The large copper anvils are used to limit the maximum temperature of the diode element to below its maximum temperature rating.

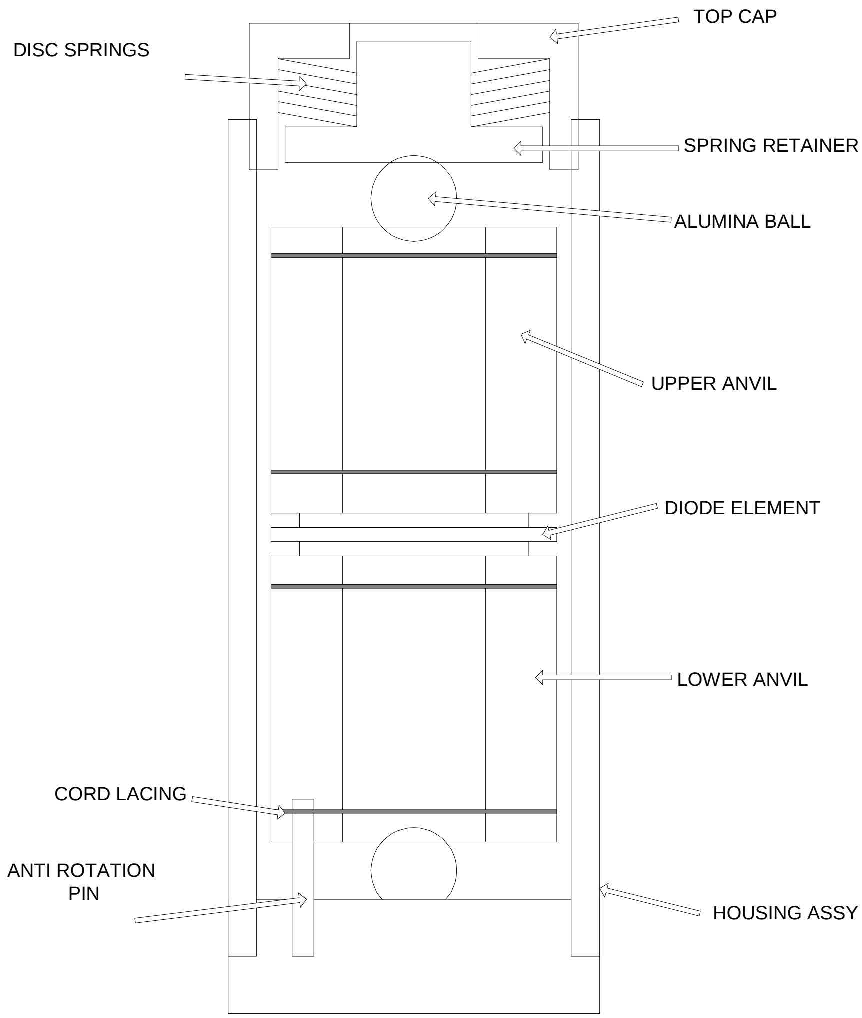


Figure 1-22 Cold Diode Assemblies.

DX Magnet

The DX dipole magnet is different than the other main magnets in two ways. First, because of its higher inductances (50 mH vs. 25 mH for an arc dipole), the induced voltage during a current ramp will be higher. This requires two series bypass diodes, instead of the single diode shown in Fig. 1-21. Second, since the DX magnet cannot absorb its own energy, an active quench protection system will be required. The active quench protection system consists of strip heaters placed along the outer diameter of the DX magnet coil and capacitor discharge power supplies that will pulse the heaters when a DX magnet quench is detected. These power supplies are located in each service building. When the strip heaters are pulsed it will cause a large area of the magnet coil to quench, this in turn will distribute the energy the magnet has to absorb to a much greater volume of the magnet coil thereby preventing any magnet damage due to overheating. To ensure high reliability of the active quench protection system for DX there are two strip heater circuits and two power supplies for every DX magnet.

Quench Detection System

The RHIC quench detection system monitors various types of superconducting magnets, shunt bus and gas cooled leads continuously to sense magnet quenches and gas cooled lead faults. The method to detect quenches is by voltage sensing, as shown in Fig.1-23 RHIC Quench Detection System Block Diagram. When a quench is determined, the system sends an quench signal for the power supplies to shutdown and energy extraction system to operate, thus protecting all essential parts of the RHIC magnet circuit.

This is a distributed system, it separates into twelve subsystems. Six subsystems locate at service buildings and the other six subsystems locate at "B" alcoves throughout the ring. Each subsystem is a standalone unit that processes its data locally. All subsystems are networked together via the Ethernet, as shown in Fig. 1-24 RHIC Quench Detection System Layout. The Control System passes Ring Events, RTDL and other parameters to the Quench System Crate controller. Data from subsystems are routed to a concentrator and archived periodically or at the time of a quench. Another PC base system containing the analysis and plotting software is also networked, allowing remote monitoring, analysis and troubleshooting of various components.

Subsystems in alcoves monitor arc-region Dipole, Quadrupole magnet voltage taps. Subsystems at service buildings monitor insertion-region magnets, shunt bus voltage taps, gas cool leads and power supply currents. Each subsystem is divided into three functional sections. The front-end computer section, ADC/timing-control section, and the low level hardware interface section.

RHIC QUENCH DETECTION SYSTEM BLOCK DIAGRAM

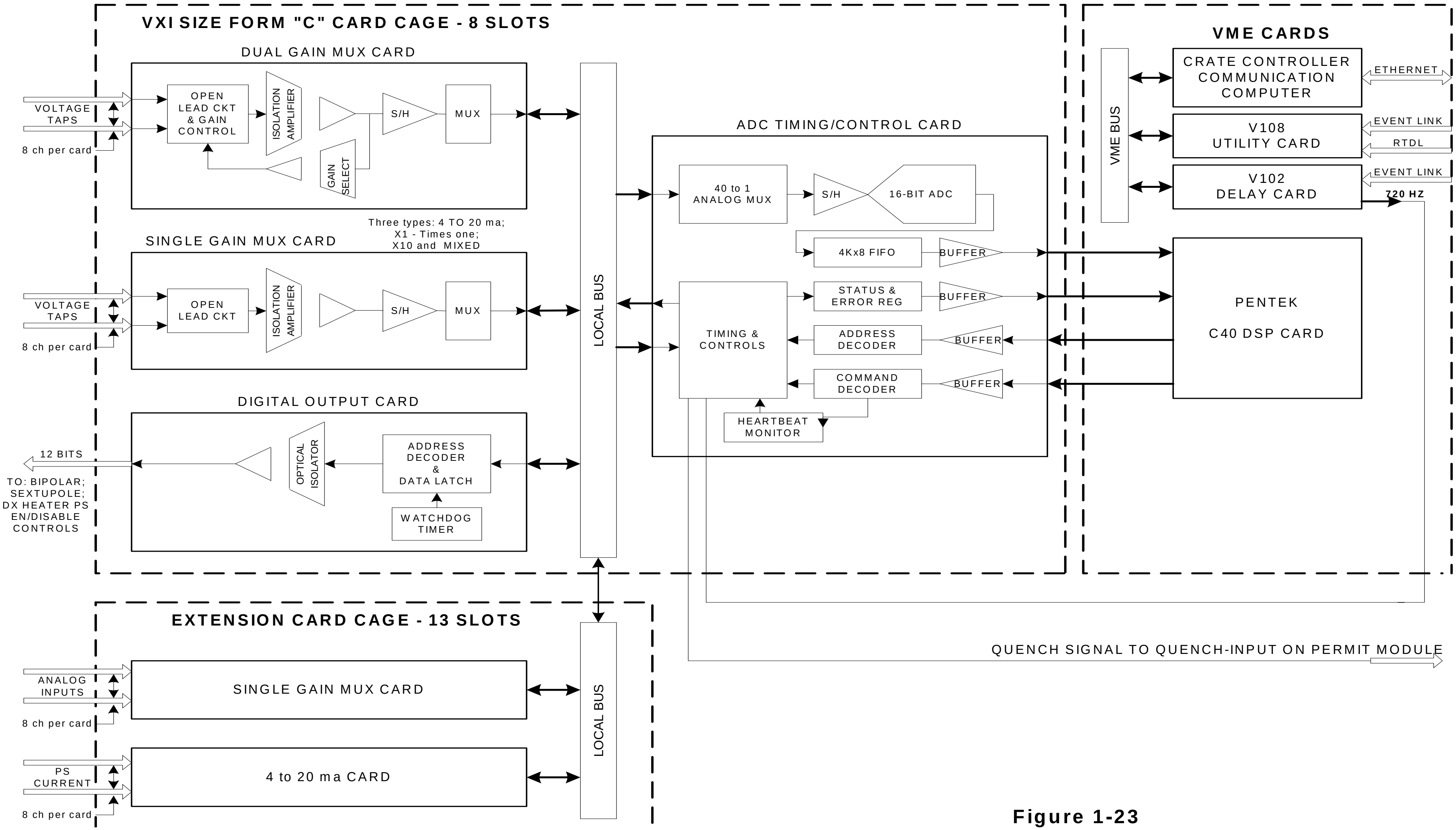


Figure 1-23

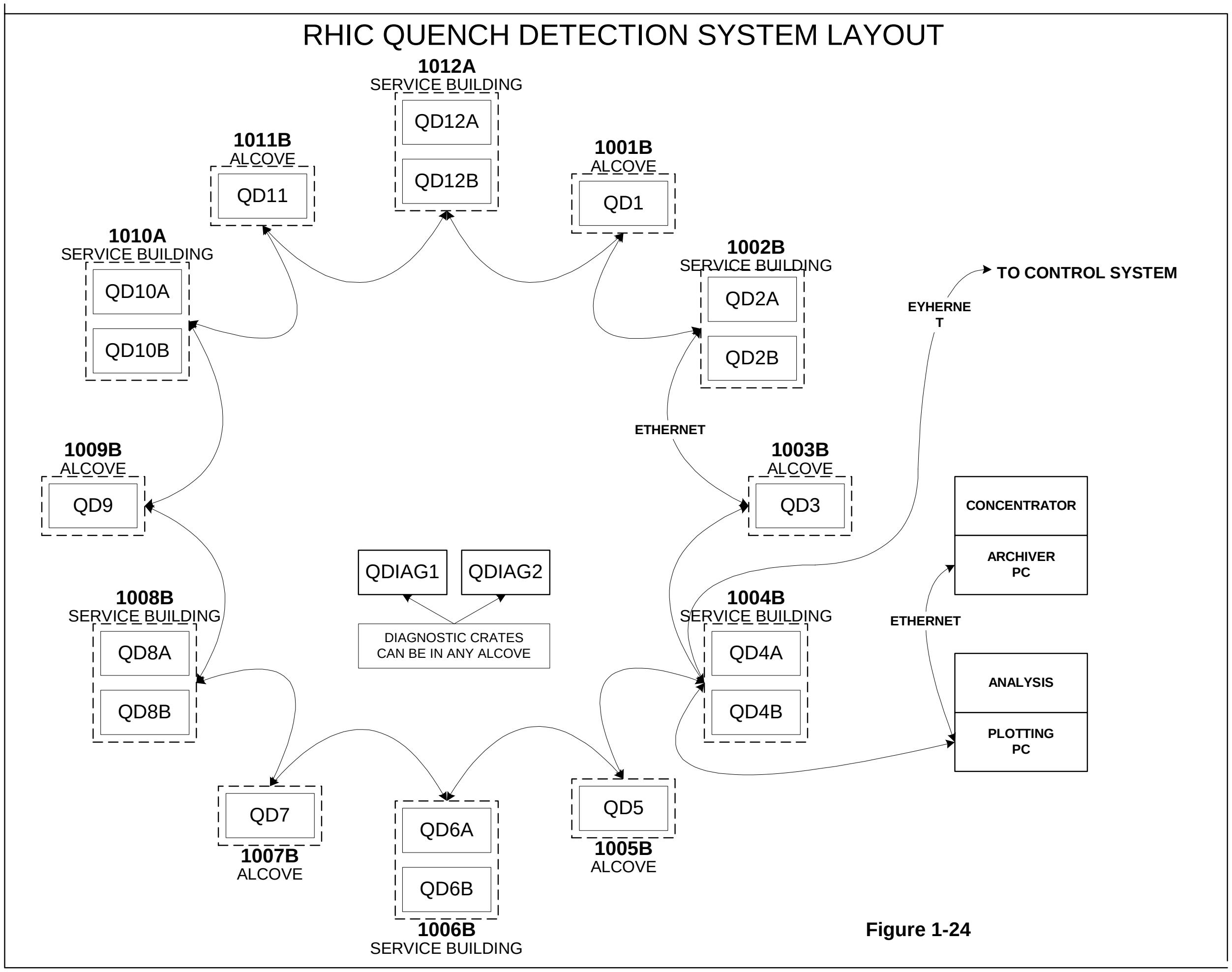

RHIC QUENCH DETECTION SYSTEM LAYOUT
1012A
SERVICE BUILDING
QD12A
QD12B
1011B
ALCOVE
QD11
1001B
ALCOVE
QD1
1010A
SERVICE BUILDING
QD10A
QD10B
1002B
SERVICE BUILDING
QD2A
QD2B
TO CONTROL SYSTEM
EYHERNE
T
ETHERNET
1009B
ALCOVE
QD9
1003B
ALCOVE
QD3
CONCENTRATOR
ARCHIVER
PC
QDIAG1
QDIAG2
DIAGNOSTIC CRATES
CAN BE IN ANY ALCOVE
1008B
SERVICE BUILDING
QD8A
QD8B
1004B
SERVICE BUILDING
QD4A
QD4B
ETHERNET
ANALYSIS
PLOTTING
PC
QD7
1007B
ALCOVE
QD6A
QD6B
1006B
SERVICE BUILDING
QD5
1005B
ALCOVE

Figure 1-24

The front-end computer section consists of a VME Crate controller, an Utility card, a Delay card and a DSP card. The function of the Crate controller is to communicate with the Control System, download programs and parameters, upload stored data to users and initialize other VME modules. The Utility card extracts Magnet Currents from the Real Time Data Link (RTDL) and passes them the DSP card. The Delay card decodes events from the Event Link and synchronizes the Quench Detection System to the 720Hz master clock at the Control system. The function of the DSP card is to read the magnet currents from the Utility card, current readback from the 4-to-20 ma card, and the magnet voltage taps signals from the analog-to-digital converter card once every 1.389ms. Noise component of 60Hz is removed by averaging twelve acquired samples. Quench condition is determined by performing calculations based on the $Vc(t) = Rc(t) * i(t) + Lc(di/dt)$ formula. Since the gas cooled lead has no resistance nor inductance, its fault is determined by comparing the voltage readback to a fixed threshold value. If the calculated $Vc(t)$ or the gas cool lead readback voltage is outside the band of the expected value that stored in the database, fault is determined. The DSP card then sends a quench signal to the Quench input of the Beam Permit Module via the ADC Card to shutdown power supplies and activate the energy extraction system.

The ADC/timing-control Card generates a simultaneously sample-and-hold signal to all low-level interface cards at the rate of 720 Hz. The holding analog signals are converted by a 16-bit scanning ADC at a fixed rate of about 10μs per channel. Converted data and hardware status are sent to a FIFO that allows the DSP to fetch data at rate up to 80ns. There is a one-second watchdog timer on the ADC card. If this timer is not reset by the DSP software, indicating the software is working properly, then the ADC card will send out the quench signal to shutdown.

There are four different types of analog interface cards to accommodate different input signals. Each card has eight analog input channels and contains open-circuit detection circuitry. The circuit sends a small negative dc current to each voltage tap. If the voltage tap or the wires to the tap are not open, then the readback is around zero volt. When the tap or the wires to the tap break or open, the sensing voltage changes to negative. This fault is sensed and reported by the DSP card to warn users that the tap is not connected correctly. The Dual Gain Mux Card connects to the Dipole and Quadrupole Magnet voltage taps. It has a gain of 0.5 in the normal mode for signals up to ±20 volts, the card automatically switches to a gain of 0.025 during quench for signals up to ±400 volts. The Single Gain Mux Card has three different versions. The X1 version accepts signals up to ±10 volts, the X10 version accepts signals up to ±1 volt, and the 4-to-20 mA version that connects to Insertion Power Supplies. There is one type of Digital Output Card to enable or disable the Bipolar, Sextupole, and DX Quench Heater power supplies. To protect the DX magnet further with hardware protection, the Digital Output card has a 20ms watchdog timer onboard. If this timer is not reset by the DSP software at the rate of less than 20ms, then the Digital Output Card will trigger the DX Heater Power Supplies and quench the DX magnet.

Energy Extraction System

Even though the individual magnet that quench is protected, it is necessary to remove the stored energy from the entire series-connected string of magnets as rapidly as possible to protect buses and diodes from overheating. The thermal mass of these elements is large enough to permit a simple solution. Figures 1-2 and 1-3 show the energy extraction systems for dipole and quadruples circuits. The main elements used in the energy extraction system for the main circuits are the SCR switches and dump resistors.

The SCR switches consists of six SCR in parallel (see Fig. 1-25). The SCR's are normally conducting when the circuit is operating normally. To insure even current sharing a current sharing resistor is in series with each SCR. The SCR's are specifically selected to have low initial turn on voltage characteristics. The current sharing resistor is size to balance the current at 6000 amps to approximately 10 percent. The switch will open when the energy stored in the pulse forming network is connected across the bank of SCR's by the trigger SCR. This will back bias the six parallel SCRs off. The voltage levels on the capacitors in the pulse forming network are fixed. This voltage level is what's required to open the switch at an operating current of 6700 amps from going through the switch. If the voltage is below this level it to will not have sufficient energy turn the SCR off. The snubber diodes stack issues to limit voltage transients when the pulse forming network is applied across the SCR bank and much lower currents (< 2000 amps). The D.C. interrupter is used as a backup in the SCR's do not open.

A PLC monitors status' and fault conditions of the SCR switch. It also performs control functions of closing and opening the switch by local and remote control.

The dump resistors are large stainless-steel resistors of sufficient mass to limit the temperature rise to acceptable limits after each energy extraction. They are cooled by natural convection. The resistance values are selected to balance the requirements of being able to remove the current fast enough to protect the cryogenic diodes or bus work and to limit the voltage transients from bus to ground and between buses during an energy extraction. The system is now designed to keep the worst-case bus quenches limited to a little over half its allowed maximum temperature rise. For the worst-case condition of a complete magnet group quenching the maximum voltage to ground is 780 volts and bus to bus voltage of 1500 volts.

The basic switch used in building 1004B in the main circuit Output Circuit Compartment (OCC) is of the same design as used in building 1010A. (same PFN, SCRs, snubber diodes stack, D.C. interrupter, interlocks, etc.) the main difference is the placement of the dump resistors across the circuits. Also there are blocking SCRs that prevent current from flowing in the dump resistors under normal power supply operation (see figure 2-2). These blocking SCR's are triggered when there is an energy extraction. The reason the SCR is a used here is the clause in main power supply can operate in the invert mode and generate a large negative voltage. If diodes reused instead of SCR's significant current would flow through the diodes when the power supply went into the invert mode.

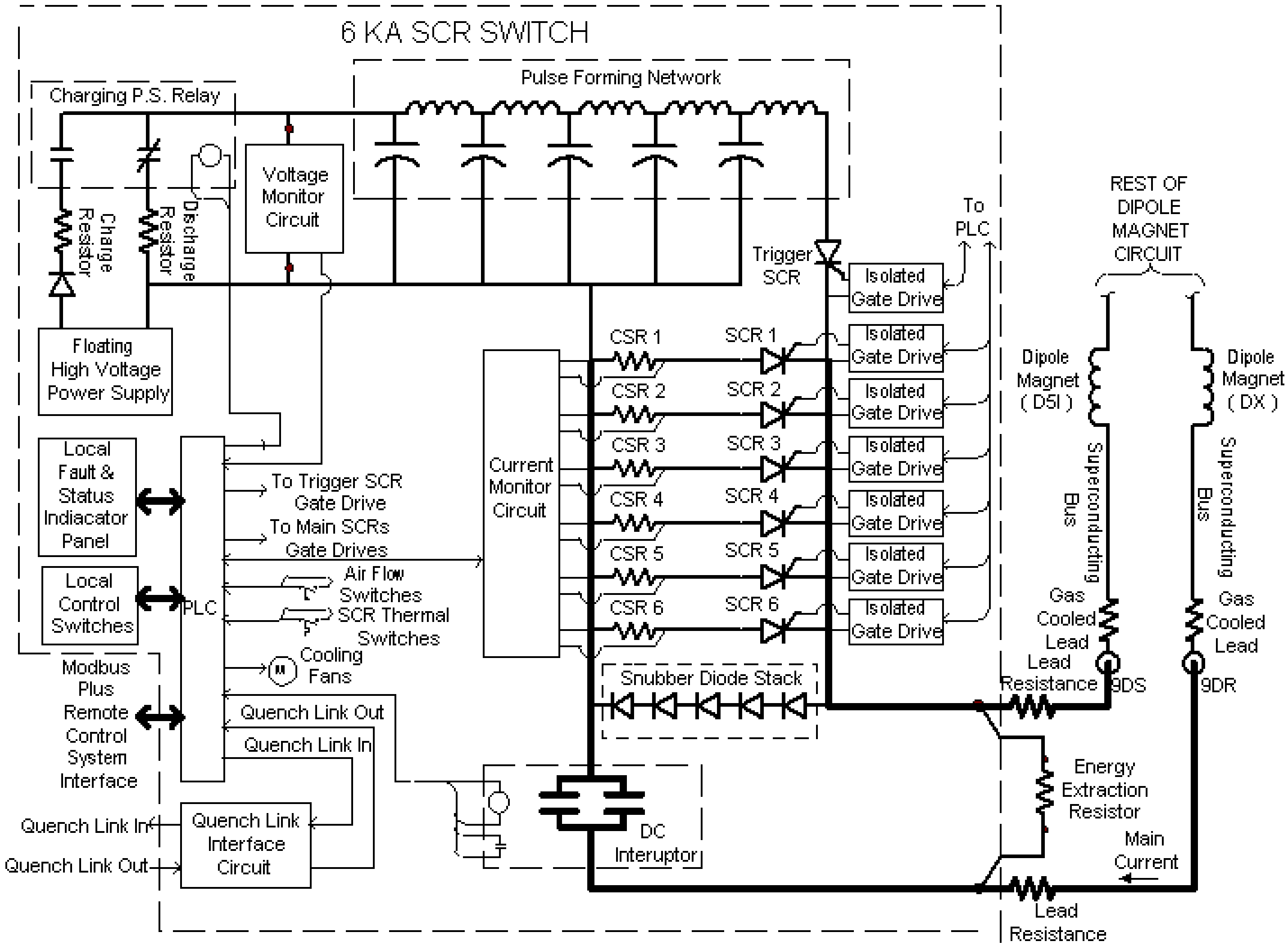


Figure 1-25 - 6KA SCR Switch Used for Dipole Circuits - Located in Bldg. 1010A

Insertion Region Circuits

The insertion region of magnet circuits of RHIC are very complex. There are power supply circuits nested within each main circuit at the six crossing regions. (See figures 1-9, 1-11) The nesting of the various circuits makes this region the most difficult to quench protect. The superconducting buses have been sized to match the nominal operating current of the shunt power supplies. At times different size conductors were used in the same circuit. With these different size conductors there are bearing limits to the amount of energy these conductors can absorb. During a bus quench one has to keep the conductors below the maximum temperature or a fault could occur. The maximum temperature limit the various depending on many factors. The most critical factor is the type of insulation used on the bus wiring. Where Tefzel is used to maximum temperature is 445 degrees Kelvin, or temperature rise of 440 degrees Kelvin. If this limit is exceeded one could get insulation failure that can cause a turn to turn short.

Current in the shunt circuits are at times significantly higher than the current in main circuit. (DX operates that 6400 amps when the arc dipole is that 5050 amps at the top energy of the machine.) During energy extraction significant voltage is undeveloped across the magnet elements. Large currents that could quench the bus will flow in the shunt buses is some action is not taken. If a bus quench work to happen the resistance growth of the quench can be so slow that in most cases it will not decrease the current fast enough to keep the energy deposited by the quench below the safe limit for that bus. Some of the shunt power supplies are configured to subtract current from the main circuit and during an energy extraction of voltage and current flow will reverse.

For all the different insertion magnet circuits there is a unique quench protection assembly (QPA) . These QPAs limit the current of its shunt bus, cause the current in its shunt bus to decrease fast enough to protect the bus, prevent excessive current flow in the power supply, and prevents excessive voltage transients from occurring during main circuit energy extraction. The QPAs are sized to match the current ratings of the various insertion region power supplies.

There are two types of QPAs , an active QPA for high inductance shunt circuits and a passive QPA for low inductance shunt circuits. (See figures 1-26, 1-27) The active QPAs use a IGBT (insulated gate bipolar transistor) switch to put a resistance in series with the shunt circuit. This will limit the current in the circuit and cause the current to decrease rapidly. If the IGBT short-circuits during an energy extraction, large currents could flow that will cause the fast acting fuse to blow and thus putting the energy extraction resistor in series with the shunt circuit. The blocking diode is to prevent large reverse currents from flowing through the internal freewheeling diode of the IGBT. The crowbar SCR prevents the current in the shunt circuit from circulating in the power supplies' output stage. It also prevents any large voltage transients that could result in a change in current direction when the main circuit is doing an energy extraction.

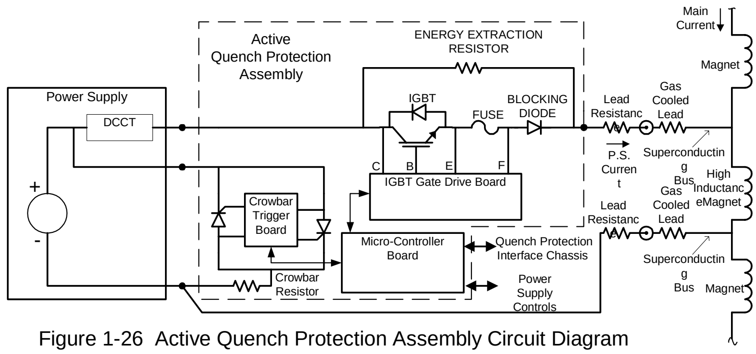


Figure 1-26 Active Quench Protection Assembly Circuit Diagram

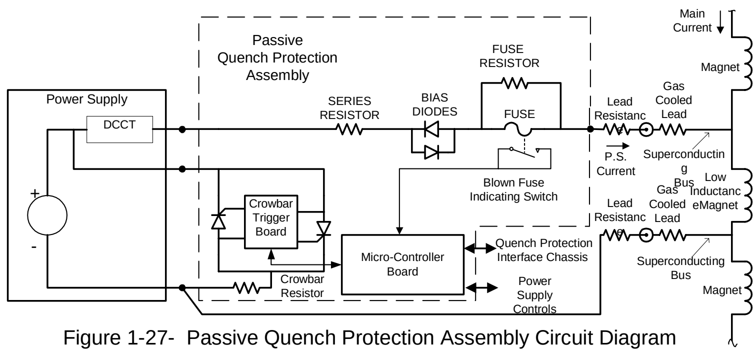


Figure 1-27- Passive Quench Protection Assembly Circuit Diagram

The passive QPAs used a simple series resistor and back-to-back biasing diodes to limit the current and enable it to decrease fast enough during the main circuit energy extraction. The fast acting fuse is also used in case there is a condition of high current (shorted crowbar SCR and/or shorted biasing diodes). The crowbar circuit functions the same way as in the active QPA.

Both active and passive QPAs have the same controls. A microcontroller monitors and reports status of interlocks and operational state of the QPAs. It also controls the IGBT and crowbar circuits by input signals from the power supply it is connected to and the quench link signal.

The Quench Protection for Trim Quads, Sextupole, and 50 Amp Corrector Circuits

The trim quad circuits have a high inductance of approximately 0.7 henrys. The single magnet that makes up the trim quad circuit is self protecting but the bus is not. The quench propagations speed of a trim quad bus quench is very slow. If a trim quad bus were to occur at maximum current the resistance growth could be too small to decrease the current fast enough to prevent damage to the trim quad bus. Therefore all trim quad magnet circuits used an active QPA to ensure that the current decreases fast enough to protect the trim quad bus.

Sextupole circuits have the largest inductance of all magnet circuits, it is approximately 9.6 henrys. The circuit consists of 12 sextupole magnets connected in series. External SCR crowbars are installed across each magnet. These SCR crowbar circuits have a self trigger circuit that will cause the SCRs to turn on when there is sufficient voltage across the magnet coil. The necessary voltage level and polarity will occur only during a magnet quench to trigger the crowbars. The SCR crowbars are amounted on a large heat sink to prevent crowbar circuit from overheating wild current interest in magnet string is brought to zero by an active QPA. This QPA has a slightly different topology then the trim quad or insertion region shunt QPAs to prevent damage of the FET output stage on sextupole power supplies. The SCR crowbars across each magnet and the active QPA also limit the maximum voltage off ground during a quench and energy extraction for the sextupole circuit. The voltage is kept under 250 volts. This relatively low value is due to a known weaknesses in the insulation of the internal bus of the sextuple magnets.

All the magnets used in the 50 amp corrector circuits are self protecting for currents up to 60 amps. Therefore the only quench protection needed for the circuits is to shut off the power supply powering them. The 50 amp power supplies have an over-voltage detection and crowbar circuit. The detection circuit will shut off the power supply when the circuit voltage exceeds a fixed limit.

Quench Link

The quench link is a ring wide interlock system that connects all the power supplies, quench detectors, and quench protection systems together. It is part of the permit module of the control system. It has two independent channels, one for the Yellow ring and one for the Blue ring. The input to the quench link to go low when a quench is detected or power supply or QPA or SCR switch develops a fault. This then causes the link's output to go down around the whole ring. When the link's output goes down it causes all the power supplies to shut off and all the quench protection switches to open up. The quench protection switches places an energy extraction resistors in series with the superconducting circuits. This causes the current in the circuits to decay to safe levels. The quench link inputs are time stamped. The quench links are located in every service building and all the center alcoves of the ring.